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ABSTRACT

This concept module on transducers is one of thirteen modules that provide a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, postsecondary technical schools. Each of the thirteen concept modules discusses a single physics concept and how it is applied to each energy system. This module discusses transducers commonly used to tranform information about mechanical, fluidal, electrical, thermal, and optical systems into an electrical or mechanical signal. Included with the concept module are fourteen application modules that discuss a specific application of a single concept in a single energy system, and contain a student laboratory exercise. Laboratory modules included are Strain Gages, Accelerometers, Bourdon Tubes, Aneroid Barometers, Differential-Pressure Transducers, Fluid-Flow Measuring Devices, Vacuum Gages, Meter Movements, Automobile Thermostats, Bimetallic Strips, Temperature Measuring Devices, Thermocouples, Thermistors, and Pyrometers. (LRA)

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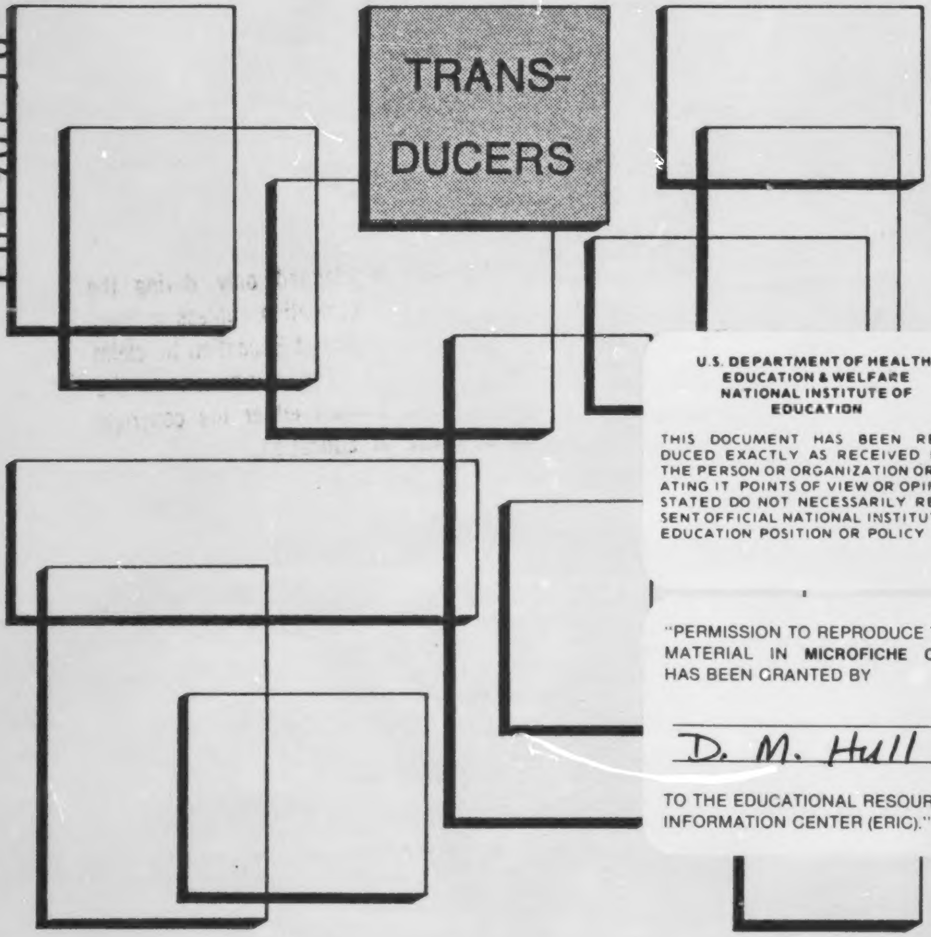
UTC

UNIFIED TECHNICAL CONCEPTS

CONCEPT MODULE 10-0

ED190758

CE 025 477



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INTRODUCTION TO UTC

Complex, modern equipment often contains combinations of hydraulic, pneumatic, thermodynamic or optical subsystems, as well as mechanical and electrical components. These subsystems and components appear not in isolation but as interdependent parts of complex systems. Consequently, a modern technician must understand not only the separate subsystems but also their interrelationships and the roles they play in an integrated system.

Since physics provides the foundation for modern technology, physics instruction in technical programs cannot be overemphasized. Physics courses for technicians should achieve three major objectives:

- Provide students with all the basic physics principles that apply to their chosen field
- Reinforce these principles through the use of "real" examples and hands-on experience.
- Organize knowledge and skills gained in a manner that provides ease of application in solving systems-oriented problems.

These objectives must be accomplished in a minimum of instructional time, and in a manner flexible enough to meet the needs of a variety of technical specialties.

Unified Technical Concepts (UTC) is a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, post-secondary technical schools. UTC organizes technical physics into 13 basic concepts (Force, Work, etc.) that apply in four "energy systems" (Mechanical, Fluidal, Electrical, Thermal). Each of the 13 "concept" modules discusses a single physics concept and how it is applied to each energy system. Similarly, each "application" module discusses a specific application of a single concept in a single energy system, and contains a student laboratory exercise.

The recommended prerequisite for UTC is one year of high school algebra, but eight supplementary modules are available for students requiring additional skills or review in the areas of math, units and graphing.

UTC is an alternate method of presenting what heretofore has been a formidable and sometimes confusing subject for technicians. It provides laboratory experiments that apply to specific technological fields, which allows a student to relate more quickly to module content - to understand how it applies to a specific technology.

UTC also represents a unique approach to teaching applied physics. Its flexible modular format allows it to be tailored by physics and technology instructors to meet specific needs of students in a specific technology.

STRUCTURE OF UTC

The modern world is based on the control and application of energy. Technology is the means by which that energy is applied to accomplish a desired task. Technical physics, being primarily a study of the physical basis of the control and use of energy, can be categorized according to the type of energy involved. Thus, in UTC, physics is divided first into four "energy systems" - Mechanical, Fluidal, Electrical and Thermal.

The same divisions are characteristic of traditional approaches to teaching technical physics. A student usually begins by studying mechanics. Once this branch of physics (energy system) is mastered, electromagnetism, thermodynamics and hydraulics are studied (one energy system at a time).

UTC takes a different approach.

CONCEPTS IN PHYSICS

The basic ideas, or "concepts," of physics appear in all energy systems, and these concepts relate to one another in similar ways in all systems. UTC unifies technical physics by presenting first the physics concept and then its application in each energy system.

The first concept studied, for example, is that of force, - the physical quantity that produces motion. The basic characteristics of force are followed by a discussion of how this concept applies to "forcelike quantities" in the following energy "systems":

- In mechanical systems force and torque cause motion of mass.
- In fluidal systems pressure difference causes motion of fluids.
- In electrical systems potential difference causes motion of mass.
- In thermal systems temperature difference causes motion of heat energy.

Problems, demonstrations and hands-on laboratory exercises are used to show the application of the concept in each energy system, and to specific devices or processes common in modern technology.

Thus, UTC provides a student with the basic concepts of physics reinforced by practical application and organized into a consistent whole; UTC is readily applied to future technical problems, whether in other courses or on the job.

COMPONENTS OF UTC

UTC incorporates three types of modules.

CONCEPT MODULES

Thirteen concept modules form the backbone of UTC (each presents a single concept in applied physics and discusses the application of that concept in each energy system):

1-0 Force.
2-0 Work.
3-0 Rate.
4-0 Momentum.
5-0 Resistance.
6-0 Power.
7-0 Potential and Kinetic Energy.
8-0 Force Transformers.
9-0 Energy Convertors.
10-0 Transducers.
11-0 Vibrations and Waves.
12-0 Time Constants.
13-0 Radiation.

APPLICATION MODULES

Each of the 170 application modules discusses the application of a single physics concept in a single energy system, and each module includes a laboratory exercise in which students investigate the application. For example, 5E5 "Resistance of Wires" (located under Concept 5-0 "Resistance"), discusses the electrical resistance of wires. In the laboratory, students calculate and measure experimentally the resistance of various wires.

SUPPLEMENTARY MODULES

In UTC, mathematics has been reduced to a minimum: one year of high school algebra is adequate preparation. The following eight supplementary modules are available for students requiring additional preparation or review:

S1 Formula Interpretation.
S2 International System of Units.
S3 Logarithms and Exponents.
S4 Angles and Triangles.
S5 Vectors and Scalars.
S6 Dimensional Analysis.
S7 Reading and Drawing Graphs.
S8 Precision, Accuracy, and Measurement.

STRUCTURE OF A UTC MODULE

Each module in UTC contains seven basic elements:

INTRODUCTION

A brief description of the topics to be discussed, and their importance in technology, introduces each module.

PREREQUISITES

A list of prerequisite UTC modules, and notice of any special knowledge or skills required for successful completion of the module, are given.

OBJECTIVES

Specific tasks that a student should be able to accomplish after completing the module are stated in behavioral terms; objectives also are the basis of testing for UTC.

DISCUSSION

This segment is an explanation of the topic to be studied. It contains the appropriate physics as well as examples of its application. The discussion includes development of equations, example problems, figures and tables of useful data. It addresses each of the objectives (except those pertaining directly to a laboratory experiment).

LABORATORY (called DEMONSTRATIONS in the Concept Modules)

The laboratory section of UTC modules consists of the following three parts:

- "Materials." A list of all equipment and supplies required for the laboratory.
- "Procedure." A step-by-step set of instructions for performing the experiment.
- "Data." An organized format for recording all necessary data and observations.

SELF CHECK

A set of questions and problems based on the module objectives is included. It is intended for use by students to check their own understanding of module content.

REFERENCES

This list of sources directs students to additional information on topics discussed in the module.

TABLE OF CONTENTS

10-1 Transducers
10M1 Strain Gages
10M2 Accelerometers
10F1 Bourdon Tubes
10F2 Aneroid Barometers
10F3 Differential Pressure Transducers
10F4 Fluid-Flow Measuring Devices
10F5 Vacuum Gages
10E1 Meter Movements
10T1 Automobile Thermostats
10T2 Bimetallic Strips
10T3 Temperature Measuring Devices
10T4 Thermocouples
10T5 Thermistors
10T6 Pyrometers

INTRODUCTION

The operation of all technical systems requires that information about those systems be made available to some controlling mechanism. An automobile, for example, may contain gages that indicate speed, fuel level, oil pressure, and temperature. Each of these gages is connected to a device called a "transducer." The transducer converts information about the conditions in the automobile into a signal transmitted to the gage, where it is displayed.

Transducers, then, are devices that accept an input signal containing information in one energy system (engine temperature, for example) and convert it into an output signal containing the same information in another energy system (displacement of a needle on a calibrated scale).

This module discusses transducers commonly used to transform information about mechanical, fluidal, electrical, thermal, and optical systems into an electrical or a mechanical signal.

PREREQUISITES

The student should have completed Concept Module 9-0, "Energy Convertors."

OBJECTIVES

Upon completion of this module, the student should be able to:

- In a short paragraph, define a transducer. Include a distinction between those transducers that require external energy sources and those that do not.
- Describe the operation of the following transducers:

  Strain gage.
  Accelerometer.
  Microphone.
  Turbine flow meter.
  Barometer.
  Meter movement.

Thermocouple.
Thermistor.
Bimetallic strip.
Photoconductive cell.
Photovoltaic cell.

DISCUSSION

To "transduce" means "to lead across." The function of a transducer is to move an information-carrying signal from one energy system to another. Transducers are called "sensors," because they provide sensory input to a monitoring or to a control system, just as human senses provide information to the brain.

Any device that transforms a signal (as described above) can be called a "transducer." Many types of transducers (electrical, mechanical, fluid, and thermal) operate in all the energy systems discussed in previous modules in this series. For each type, transducer function remains the same: to transform information from one system form to another.

Transducers can be regarded as having an input and an output (Figure 1). The transducer (shown as a box) accepts some input quantity, which may represent a physical property, and produces an output, which is the response of the transducer to that property.

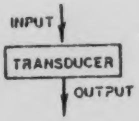


FIG. 1

An electrical input (Figure 2) and a mechanical output illustrates this principle more specifically. In this example, input is an electrical current; the transducer is an ammeter; and the output is the mechanical deflection of the needle on the meter.

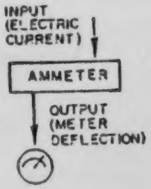


FIG. 2

Output usually varies with input, thus giving a transducer a capability as a measuring device. For example, voltage (or current) output from a photocell is indicative of the amount of light energy incident upon the photocell. Thus, a photocell may be used as a quantitative detector of light energy.

Another aspect of a transducer is that it must be capable of transmitting, as well as transforming, a signal. A transducer often operates on waves or currents (e.g., light waves, acoustic waves, or electric currents). Again, the photocell provides an excellent example: it receives light waves and emits electrical currents.

Some transducers actually are energy convertors; that is, they convert the energy of the input signal directly into energy of the output signal. The photocell described above is an example. When light strikes the photocell, some of the light energy is converted directly into electrical energy; therefore, any of the energy convertors discussed in Concept Module 9-0, "Energy Convertors," can be used as transducers. One advantage of this type of transducer is that it requires no external energy source for operation.

Other transducers do require an external energy source of their own. In most cases, this source is in the form of an electrical current through an element, whose resistance changes in response to some physical quantity. This type of transducer does not convert one type of energy directly into another; it changes its resistance in response to the input energy and, thus, changes the rate of flow of some quantity through itself. Most such transducers operate on electrical power, but a few devices using fluid flow as an external energy source also are used in some fluidal-control systems.

The remainder of this module discusses a variety of transducers. They are classified according to the energy systems in which the input signals originate. In all cases, the output signal is either electrical (current or voltage) or mechanical (position of an indicator).

MECHANICAL TRANSDUCERS

MICROPHONE

The most common device for changing a mechanical vibration wave to an electrical wave is the microphone.

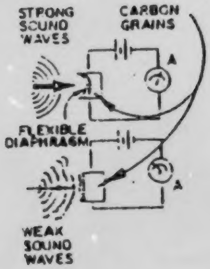


FIG. 3

Different types of microphones employ different physical principles of operation. One widely-used type is the carbon microphone, which contains a diaphragm that moves (vibrates) in response to acoustic waves incident upon it (Figure 3). Immediately behind (and in contact with) the diaphragm is a small cup filled with tiny grains of carbon. A low-voltage electrical current passes through these carbon grains. When the diaphragm moves in response to sound waves pressing on it, electrical resistance in the carbon medium changes, and electric current through the carbon varies accordingly. If the sound is intense, pressure on the diaphragm increases, pressing the carbon grains together more tightly.

Because highly-compressed carbon offers less resistance than loosely-packed carbon, the amount of electricity flowing through them increases. If sound is weak, only a light pressure is incident upon the diaphragm, and the grains are loosely-compacted; therefore, resistance is high, and less electric current flows through the carbon.

The diaphragm and the carbon grains form a transducer, changing acoustic waves into varying electrical current. And, although such a carbon microphone does not exhibit high fidelity, it does represent a good example of a transformer for sound energy into electrical energy. (Other, more sophisticated, microphone types convert sound more faithfully.)

PIEZOELECTRIC PRESSURE TRANSDUCER

Some types of crystalline material exhibit a phenomenon called "piezoelectric effect." When mechanical pressure is applied to certain crystal types, they are strained, or slightly deformed. This strain causes an electric charge to appear on certain surfaces of the crystals (Figure 4).

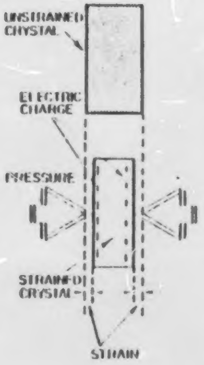


FIG. 4

Application of pressure results in strain, causing electrical charge of opposite polarity to appear on the two surfaces. (In reality, a complicated relationship exists between the direction of the applied force, the crystalline structure, and the surfaces on which the charge appears. Because this relationship is beyond the scope of this module, a simplified version is presented.)

When pressure is released, the charge disappears rapidly. Thus, a piezoelectric crystal must be considered a transducer of mechanical energy into electrical energy. The charge on the surface leads to a voltage in an electric circuit connected to the crystal. Thus, the crystal can be used as a pressure sensor. Quantitative measurement can be made of the pressure if the voltage is measured.

A piezoelectric crystal also can serve, in reverse, as a transducer of electrical energy into mechanical energy; that is, voltage applied to a piezoelectric crystal causes it to undergo deformation and to exert mechanical pressure.

The piezoelectric effect is observed only in certain types of crystals; for example, in Rochelle salt (sodium potassium tartrate) and in tourmaline (a semiprecious gem). Significant properties of several piezoelectric crystals, summarized in Table 1, include voltage that can be obtained in an open electrical circuit for unit applied pressure and for unit thickness.

TABLE 1. PIEZOELECTRIC CRYSTAL PROPERTIES

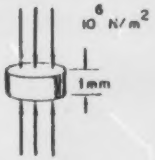
Crystal	Voltage Per Unit Thickness Per Unit Applied Pressure $\frac{\text{volt} \times \text{meter}}{\text{newton}}$	Coupling Coefficient k (Efficiency)
Quartz	0.055	9.9%
Rochelle salt (at 30°C)	0.098	78%
Ammonium dihydrogen phosphate	0.178	25%
Ethylene diamine tartrate	0.152	21.5%
Lithium sulfate	0.165	35%
Tourmaline	0.0275	9.2%

The coupling coefficients (Table I) are efficiencies for conversion of electrical energy into mechanical energy. Values listed are obtainable only with careful design; but, as Table I shows, values can be quite high. Thus, under certain conditions, piezoelectric transducers can be efficient convertors of mechanical energy into electrical energy.

Piezoelectric crystals have many applications, but usually are employed in dynamic conditions, in which there are changing pressures or accelerations. Under steady conditions, when a static force is applied, the charge gradually leaks off the surface. Piezoelectric crystals can be found, therefore, in dynamic devices, such as phonograph pickups, high-quality microphones, accelerometers, and ultrasonic submarine detectors.

EXAMPLE A: CALCULATION OF PIEZOELECTRIC VOLTAGE

Given: A pressure of 10^6 newton/meter^2 is applied to a piezoelectric crystal of ammonium dihydrogen phosphate 1 mm thick.



Find: Resulting open circuit voltage.

Solution: From Table 1, voltage per thickness per unit applied pressure is given for ammonium dihydrogen phosphate as 0.178 volt x meter/newton. Voltage is given by

$$V = kpt$$

where

k = coupling coefficient.
p = pressure on crystal.
t = time.

Therefore –

$$V = \left(0.178\ \frac{\text{volt x meter}}{\text{newton}}\right)\left(10^6\ \frac{\text{newton}}{\text{meter}^2}\right)\left(0.001\ \text{meter}\right)$$

$$V = 178\ \text{volts}$$

STRAIN GAGES

Strain gages are used to measure dimensional changes in a sample of material. A strain gage consists of a resistive element whose resistance changes in response to the strain of the element. The resistance of a wire was described in Concept Module 5-0, "Resistance," by Equation 1.

$$R = \frac{\rho \ell}{A} \qquad (1)$$

where

R = resistance.
ρ = resistivity of material.
ℓ = length of conductor.
A = cross-sectional area of conductor.

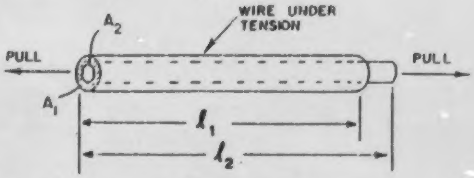


FIG. 5

If the shape of the conductor changes, as shown in Figure 5, then both A and ℓ change, producing a change in the resistance of the conductor. The strain gage is connected to a constant-voltage source; thus, a change in its resistance causes a change in the current through the gage. This change in current is proportional to the strain of the material to which the strain gage is bonded.

OTHER MECHANICAL TRANSDUCERS

Other mechanical transducers include phonograph needles and cartridges and position sensors, in which a position of an object is transformed into an electrical signal by a change in the value of a variable resistor. In rotational systems, mechanical rotational energy often is converted to electrical energy by a generator. Examples of this appear as an intermediate step in some of the fluidal transducers discussed in the following section.

FLUIDAL TRANSDUCERS

TURBINE (FLUID) FLOWMETER

"Turbine flowmeters" are devices inserted into a pipe or tube to measure the rate of fluid flow. A multi-bladed turbine (Figure 6) rotates in proportion to the velocity of the fluid flow past its blades. A coil of wire is placed next to the outside of the pipe. As the magnet rotates, it generates a short pulse of current in the coil.

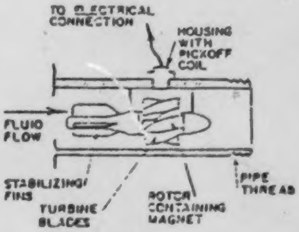
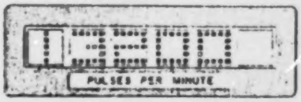


FIG. 6

This method of sensing relies upon electromagnetic induction, a phenomenon discovered by Michael Faraday in 1831. Motion of the magnet induces a voltage, therefore a flow of current, in a nearby coil of wire.

Because of electromagnetic induction, fluid flow through the pipe generates an electrical pulse at a rate proportional to the flow. Each pulse represents passage of a known volume of fluid past the rotor. The cumulative pulses can be fed directly into a digital display that indicates total flow. Also, the pulses can be used to drive an electrical meter to indicate flow rate. Such devices are important in industry for measuring, recording, and controlling flow of chemicals, petroleum, cryogenic liquids, and the like. The following example shows how a known calibration can be converted into a flow rate.

EXAMPLE B: CALCULATION OF FLOW BY FLOWMETER



Given: A commercial turbine flowmeter is calibrated (by number of pulses registered by pickup coil per unit volume of liquid passing through the turbine) at 1200 pulses per gallon and registers 13,200 pulses per minute.

Find:
(1) Flow rate.
(2) Flow (in gallons) in 6-minute period.

Solution: 13,200 pulses/minute x 6 minutes = 79,200 pulses

Total flow = 79,200 pulses ÷ 1200 pulses/gallon
= 66 gallons in 6 minutes

Flow rate = 66 gallons/minute/6 minutes
= 11 gallons/minute

This same principle is used in a device called an "annemometer," used to measure wind velocity.

PRESSURE-SENSING DEVICES

Figure 7 displays the parts of a barometer used to measure atmospheric pressure. The aneroid capsule is a flexible, sealed metal can. When the external pressure changes, the height of the capsule changes. This displacement is converted into a needle deflection by a gear drive. In some cases, the gear drive is connected to a variable resistor to transform the output into an electrical signal.

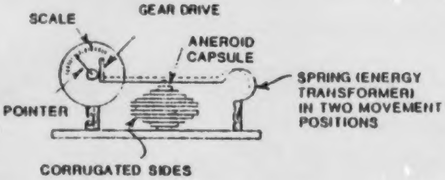

SCALE
GEAR DRIVE
ANEROID CAPSULE
SPRING (ENERGY TRANSFORMER) IN TWO MOVEMENT POSITIONS
POINTER
CORRUGATED SIDES

FIG. 7

The Bourdon tube (Figure 8) also transforms a pressure change into a needle deflection. As pressure in the tube increases, the free end moves upward; a decrease in pressure causes a downward movement.

ELECTRICAL TRANSDUCERS

METER MOVEMENT

Figure 9 illustrates the construction of a meter movement that transforms the magnitude of an electrical current into the deflection of a needle on a scale. The meter consists of four basic parts: (1) A permanent magnet provides a constant magnetic field. (2) A coil of wire is wrapped around (3) an iron cylinder suspended in this field. (4) A coil spring is arranged to hold the needle of the meter at zero when no current passes through the coil. When a current flows through the coil, a magnetic field is produced at an angle to the field of the permanent magnet. The magnetic forces produced rotate the movable coil and cylinder until the torque applied by the spring balances that applied by the magnetic field.

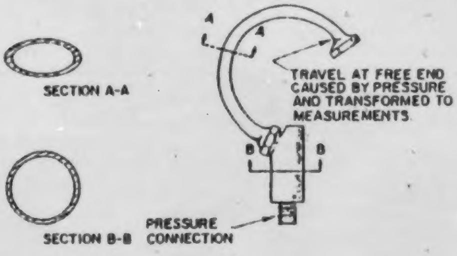

A
A
SECTION A-A
TRAVEL AT FREE END CAUSED BY PRESSURE AND TRANSFORMED TO MEASUREMENTS
B
B
SECTION B-B
PRESSURE CONNECTION

FIG. 8

The scale of the meter can be calibrated to provide measurement of any quantity proportional to the current through the meter coil. Such meter movements are used widely in all areas of technology.

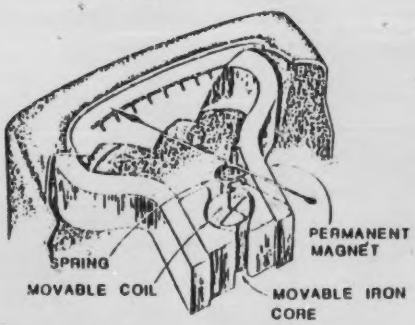

PERMANENT MAGNET
SPRING
MOVABLE COIL
MOVABLE IRON CORE

FIG. 9

THERMAL TRANSDUCERS

THERMOCOUPLE

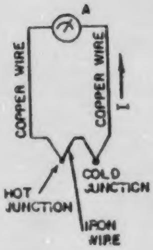


FIG. 10

A thermocouple, an extremely simple transducer, transforms thermal energy into electrical energy. Widely-used for temperature sensing, thermocouples depend upon the fact that electrical current flows in a circuit of two different metals (provided the metals are joined to form a complete circuit, and provided the two junctions are kept at different temperatures). In a thermocouple formed of copper and iron wires, if cold junction is kept at 0°C, and if the other junction is heated, current flows as indicated in Figure 10. Current flow shows that an electromotive force (voltage) exists between the two junctions. This voltage, produced by temperature difference, is typically small — on the order of a fraction of a millivolt for a temperature difference of 1°C.

Because voltage varies with temperature differences, thermocouple transducers make excellent temperature-measuring devices.

A third metal in the circuit does not change the voltage if its junctions are at the same temperature. Thus, a measuring device, such as a voltmeter or potentiometer, can be inserted into a circuit without affecting its voltage.

In practice, temperature of one junction is kept at a known, fixed temperature. This set temperature can be obtained, for example, if the cold junction is immersed in an ice-water bath at 0°C. Then the unknown temperature of the other junction can be derived from the measured voltage.

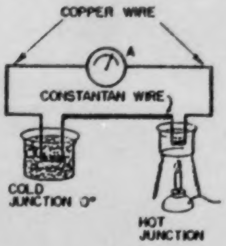
Approximate voltage values that can be expected from various pairs of metals when the cold-junction temperature is 0°C are shown in Table 2.

Example C makes use of data given in Table 2 and shows use of a thermocouple as a temperature-measuring device.

TABLE 2. APPROXIMATE VOLTAGE VALUES FOR CERTAIN THERMOCOUPLES (COLD JUNCTION AT 0°C)

Metals	Useful Temperature Range (C°)	Voltage (Millivolts/C°)
Iron-constantan (60% Cu - 40% Ni)	0 to 800	0.050
Chromel-alumel	300 to 1300	0.040
Platinum/rhodium-platinum	600 to 1500	0.009
Copper-constantan	-200 to 400	0.040

EXAMPLE C: THERMOCOUPLE JUNCTION TEMPERATURES



Given: A copper-constantan thermocouple, with its cold junction at 0°C, registers a voltage of 4.8 millivolts.

Find: Temperature of the other junction.

Solution: From Table 2, a temperature difference of 1 C° produces 0.04 millivolts. Thus, the temperature difference between the junctions is 4.80/0.04 = 120 C°. Because the cold junction is at 0 C°, the other junction is at 0 + 120 C° = 120 C°.

OTHER TEMPERATURE-MEASURING DEVICES

Several additional temperature-measuring devices are in common use. In an ordinary thermometer, the level of a liquid in a capillary tube indicates the temperature of the liquid and its surroundings. A thermistor is a resistive element whose resistance changes in response to its temperature. A bimetallic strip consists of two strips of different metals bonded together. As the temperature of the strip increases, one metal expands more rapidly than the other, causing the strip to bend. This type of thermal sensor is used widely in the thermostats controlling industrial and residential heating and cooling systems.

OPTICAL TRANSDUCERS

PHOTOCONDUCTIVE PHOTOCELL

A photoconductor is a transducer of the intensity of optical (light) energy into electrical voltage or current (Figure 11). The sensitive element in a photoconductor is a semiconductor, such as silicon. Bias voltage applied across a semiconductor causes electrical current to flow through a load resistor. Because the semiconductor typically has low electrical conductivity, current is small when a semiconductor is in the dark. But light falling upon the semiconductor releases free electrons within the semiconductor; electrical conductivity increases, causing current to increase and, according to Ohm's law ($V = IR_L$), voltage V to increase.

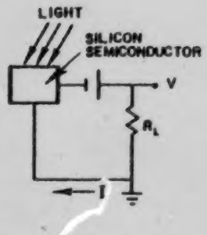


FIG. 11

Although the output appears primarily as a forcelike quantity (voltage), it may be used to drive current in an external circuit.

PHOTOVOLTAIC CELL

The photovoltaic cells described in Concept Module 9-0, "Energy Convertors," and mentioned earlier in this module also are used as optical-to-electrical transducers. Unlike photoconductive cells, photovoltaic cells produce their own voltage by a conversion of optical energy into electrical energy. They require no external voltage source when operated in the photovoltaic mode. These devices also can be connected in a biasing circuit similar to Figure 11 and operated in the photoconductive mode. This connection is made to improve both sensitivity and response time.

SUMMARY

A transducer is a device capable of accepting an input signal containing some information from one energy system and of producing an output signal containing the same information in another energy system. Some transducers are energy convertors that convert input energy to output energy. These transducers require no external energy source. Others change their resistance in response to the input and, thus, change the rate of flow of some quantity, usually of electric current. This second class of transducers requires an external energy source to supply the current to the transducer.

There always is a relationship of the output of a transducer to its input. For example, as temperature increases, voltage output of a thermocouple increases; as fluid flow increases, the counting rate of a turbine flowmeter increases. In other words, the output of a transducer gives a quantitative indication of its input. For this reason, transducers are used widely as measuring devices (in science, engineering, and industry) of diverse quantities (temperature, pressure, flow rate, illumination levels, and so on).

TEMPERATURE MEASUREMENT

MATERIALS

Commercial thermocouple (copper-constantan or equivalent).
Millivoltmeter.
Watch or clock.
Bunsen burner.
Ring stand and clamp.
Two beakers.
Water and ice.
Wiring and clips for electrical connections.
Graph paper.

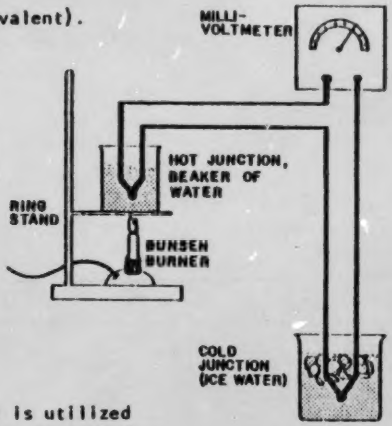


FIG. 12

PROCEDURE

In this experiment, a thermocouple transducer is utilized to measure temperature of water in a beaker as water is heated.

1. Set up apparatus (Figure 12). The cold junction contains mixture of water and ice at 0°C. The hot junction is in beaker of water heated by a bunsen burner. (Use one of thermocouples listed in Table 2.)

2. Record initial reading of millivoltmeter: ____________.

3. Light bunsen burner; begin heating water.

4. Record reading of millivoltmeter at one-minute intervals as water heats: ____________.

5. When water begins to boil, record final reading of millivoltmeter; turn off bunsen burner: ____________.

6. Calculate water temperature for every recorded value of voltage; use value from Table 2 for response of particular thermocouple.

7. On graph paper, record temperature versus time; compare final value with known boiling temperature of water.

CONVERSION EFFICIENCY

MATERIALS

Electrically powered horn.
Battery or d.c. voltage supply.
Switch.
Ammeter.
Commercial piezoelectric microphone pressure transducer.
Oscilloscope.
Wiring for electrical connections.
Meter stick.

PROCEDURE

This experiment requires two transducers — a horn (electrical-to-mechanical) and a piezoelectric pressure sensor (mechanical-to-electrical). Measure efficiency of conversion of electrical energy into acoustic energy.

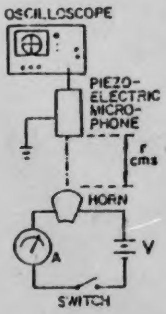


FIG. 13

1. Connect apparatus (Figure 13). The piezoelectric transducer (microphone) can be about 1/3 meter from horn.

2. With meter stick, measure distance r (in cm) from horn to piezoelectric transducer microphone. Record here: __________.

3. Close switch to activate horn; measure current I (through horn) with ammeter A. Record here: __________.

4. Measure voltage produced by piezoelectric transducer. (Use oscilloscope.) Record voltage: __________.

5. Open switch to turn off horn.

6. Calculate pressure p at piezoelectric transducer; use manufacturer's calibration of voltage versus pressure.

7. Calculate energy per unit time in sound wave:

$$\text{Energy per unit time} = 4 \times 10^{-7}\ \pi r^2 p^2/\rho c$$

NOTE: In the above equation, energy per unit time is in joules per second, r is in cm, and p (from Step 6) is in dyne/cm^2. Use known values of $\rho = 0.00129$ g/cm^3 for density of air and $c = 3.32 \times 10^4$ cm/s for velocity of sound in air. The above formula is an approximation; it assumes that sound spreads equally in all directions from horn. (Because horn probably has directional properties, formula may not be strictly accurate, but is sufficient for this experiment.)

8. Calculate electrical energy (per unit time) delivered to horn. This value is given (in joules per second) by product of voltage V (volts) time current I (amps) from horn circuit.

9. Determine efficiency (η) of conversion of electrical energy into acoustic energy by dividing result of Step 7 by result of Step 8.

FLOW MEASUREMENT

MATERIALS

Turbine flowmeter — covering range of ≃ 5 gal/min. (Model 4900-12 with model 4100 meter readout from Brooks Instrument Division, Emerson Electric Company, or equivalent).
Cold-water supply.
Tubing and connectors or hose clamps, as needed.
Stopwatch.
Pail (capacity of at least 5 gallons).

PROCEDURE

In this experiment, a turbine flowmeter will be employed as a transducer to measure flow of water.

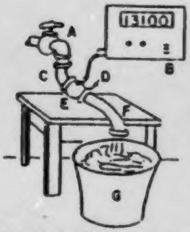
1. Connect flowmeter to cold water tap; use rubber tubing and clamps as needed (Figure 14); connect indicating unit to flowmeter; direct output of final length of tubing into the pail; mark 5-gallon capacity on inside of pail.

2. Quickly turn on cold water; simultaneously start stopwatch.

3. Observe and record reading of flowmeter indicator: ________.

4. When water reaches 5-gallon mark, stop stopwatch and record reading of flowmeter indicated: ________.

5. Calculate flow rate (gal/min): 5 gallons divided by time (in minutes) to fill pail: ________.



A- COLD WATER TAP
B- INDICATING UNIT
C- TUBE
D- HOSE CLAMPS
E- FLOW METER
F- TUBE
G- 10-GALLON PAIL

FIG. 14

6. Compare results (from Step 5) with flow measured in Steps 2 to 4.

7. Discuss differences, if any.

SELF CHECK

1. Describe the function of a transducer.

2. Describe the differences between transducers that convert input energy directly into output energy and those that do not. Give an example of each type in the following energy systems:

   Mechanical.
   Fluidal.
   Thermal.
   Optical.

3. Describe the operation of the following transducers:

   Meter movement.
   Microphone.
   Accelerometer.
   Barometer.
   Thermocouple.
   Photovoltaic cell.
   Bimetallic strip.
   Strain gage.
   Turbine flow meter.
   Thermistor.
   Photoconductive cell.

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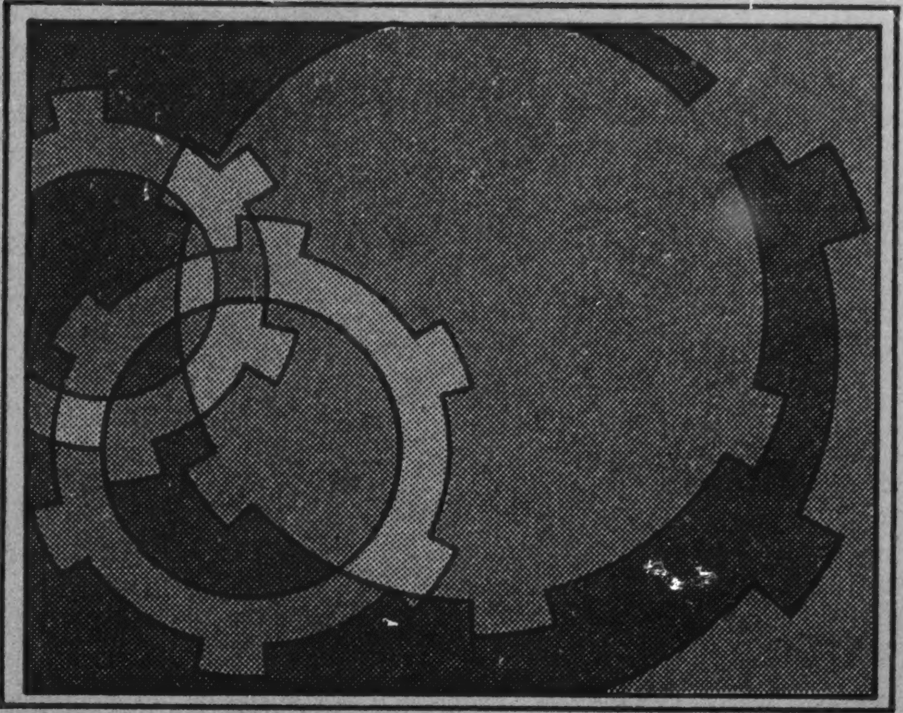
UNIFIED TECHNICAL CONCEPTS

MODULE 10 M 1

STRAIN GAGES



MECHANICAL APPLICATION OF TRANSDUCERS

Technical Education Research Center-Southwest TERC-SW

INTRODUCTION

The strain gage is a transducer device used in the measurement of small dimensional changes in a surface. It consists of a fine wire winding (or of foil or semiconductor materials) bonded firmly to the surface tested. As the surface deforms under strain, so does the strain gage, causing the dimensions of the wire to undergo change and, therefore, to change its electrical resistance. This change in resistance is measured to determine the strain experienced by the sample.

This module introduces the construction and operation of various strain gages. In the laboratory, the student will measure the change in resistance of a wire subjected to strain, and will use a strain gage to measure a sample strain.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Briefly describe operation of a strain gage.
- Define the term "gage factor" and state ideal and typical real values for the gage factor.
- List the three types of materials used for strain gages and at least one specific metal alloy used.
- Calculate the gage factor of a wire, given the wire resistance, strain, and increase in resistance.
- Given the appropriate equipment, measure the change in resistance of a wire under tensile stress, and measure strain in a metal bar to which force is applied.

DISCUSSION

A strain gage is a device used to measure dimensional changes in a sample of material. The strain gage consists of a material whose electrical properties change as it is stretched or deformed. For example, a length of fine wire under tension will undergo a slight dimensional change accompanied by a change in electrical resistance of the wire. If the wire is bonded firmly to the sample, measurement of change in electrical resistance of the wire can be used to determine strain in the sample.

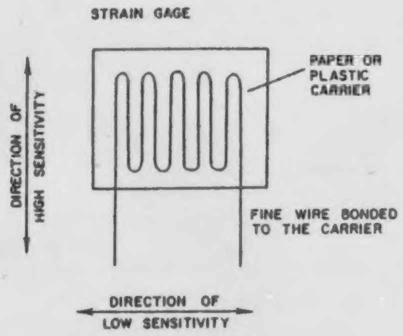

STRAIN GAGE
PAPER OR PLASTIC CARRIER
DIRECTION OF HIGH SENSITIVITY
FINE WIRE BONDED TO THE CARRIER
DIRECTION OF LOW SENSITIVITY

FIG. 1

TYPES OF STRAIN GAGES

Strain gages take a number of forms: thin wires, foils, or semiconductors. A typical form for a wire strain gage is shown in Figure 1. The fine wire is first bonded to a carrier material (e.g., paper or plastic) by cement. One particular shape for the wire is shown in Figure 1, but configurations in a wide variety are used in modern strain-sensitive elements. The gage then can be cemented to the sample. When the sample is strained, strain is transmitted to the strain gage. Measurement of electrical resistance of the wire gives the strain in the wire and, therefore, the strain in the sample to which it is bonded.

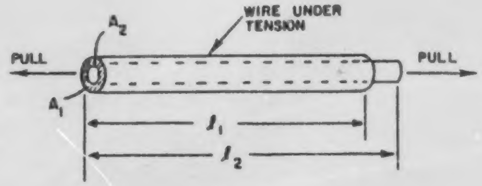

A_2
WIRE UNDER TENSION
PULL
PULL
A_1
l_1
l_2

FIG. 2

Figure 2 illustrates how the strain of a wire affects its electrical resistance, and defines length and cross-sectional area of a wire before it is strained. When the wire is strained, it becomes slightly longer, and the cross-sectional area becomes smaller. Electrical resistance before the wire is strained is given by Equation 1.

$$R_1 = \frac{\rho \ell_1}{A_1} \qquad (1)$$

where
R_1 = electrical resistance of wire before being strained.
ρ = electrical resistivity of wire.
ℓ_1 = length of wire before being strained.
A_1 = cross-sectional area of wire before being strained.

If the assumption is made for the moment that electrical resistivity is unaffected by strain, resistance after strain is applied is given by Equation 2.

$$R_2 = \frac{\rho \ell_2}{A_2} \tag{2}$$

where
R_2 = electrical resistance of wire after being strained.
ℓ_2 = length of wire after being strained.
A_2 = cross-sectional area of wire after being strained.

Thus, resistance changes because of dimensional changes in the wire. The wire becomes longer as it is strained, and the cross-sectional area decreases; both of these changes affect the electrical resistance, according to Equations 1 and 2.

Change in electrical resistance is related to strain, as given in Equation 3.

$$\frac{\Delta R}{R} = \frac{\Delta \ell}{\ell}(1 + 2\nu) = S(1 + 2\nu) \tag{3}$$

where
ΔR = change in original resistance R due to a change $\Delta\ell$ in original length ℓ.
ν = an elastic constant called Poisson's ratio. (Refer to next paragraph.)
S = strain, equal to $\Delta\ell/\ell$.

Poisson's ratio ν varies slightly in value from one metal to another. For most metals, it is approximately equal to 0.3, which will be used in this module.

Since $\Delta\ell/\ell$ is recognized as strain S — a dimensionless quantity given sometimes as "inches per inch" or "centimeters per centimeter" — Equation 3 can be rewritten as shown in Equation 4 where the gage factor G is introduced.

$$\frac{\Delta R}{R} = GS \tag{4}$$

where
G = gage factor, $1 + 2\nu$.

Equation 4 is used to solve a problem in Example A.

Definition of the gage factor G follows from Equation 4. G is equal to fractional change in resistance $\Delta R/R$ divided by strain $S = \Delta \ell/\ell$; thus, the gage factor is a fractional change in resistance per unit strain. Since G is equal to $(1 + 2\nu)$, and ν for most metals is equal to 0.3, ideally the gage factor should equal 1.6. However, Equations 3 and 4 were derived on the assumption that electrical resistivity $\rho = RA/\ell$ does not change with strain. This is not quite true. Electrical resistivity ρ does change with strain in a rather complicated manner. When this change is taken into account, the gage factor G is typically found to have values in the range from $G = 1.8$ to $G = 4.5$ rather than the simple value of 1.6 given above.

To summarize, the relationship between fractional change in resistance and strain S is given by Equation 4. Ideally, G should have the value 1.6, but in practice the value of G will vary between 1.8 and 4.5 because of the change of electrical resistivity with strain (see Example A).

EXAMPLE A: RESISTANCE CHANGE CALCULATION

Given: A strain gage has a resistance of 1000 Ω; gage material has a value of modulus of elasticity of 10^{12} dyne/cm^2 and is subjected to a stress of 10^9 dyne/cm^2.

Find: Change in resistance.

Solution: Strain S is found from Equation 5:

$$E = \frac{P}{S}$$

$$S = \frac{E}{P}$$

where

P = stress.
E = modulus of elasticity.

Using values above,

$$S = \frac{10^9}{10^{12}}$$

$$S = 10^{-3}$$

Then, using Equation 4, change in resistance ΔR is derived as follows:

$$\frac{\Delta R}{R} = GS$$

$$\Delta R = GSR$$

$$\Delta R = 2 \times 10^{-3}\ (1000\ \Omega) = 2\Omega$$

MATERIALS AND CONSTRUCTION OF STRAIN GAGES

Strain gages can be made of three different types of materials:

Small-diameter wire (about 0.001 inch diameter).
Thin sheets of metal foil (about 0.00015 inch thick) etched to form patterns similar to that in Figure 1.
Semiconductor materials, basically similar to metallic gages, but giving greater response for a given strain.

The arrangement for strain-gage design shown in Figure 1 gives relatively high sensitivity to strain along the length of the loops of wire and low sensitivity to strain perpendicular to that direction. For two-dimensional measurements, two separate, electrically insulated, gages, oriented in two perpendicular directions, can be used.

Commercial strain gages come with the sensitive element mounted on a carrier or backing, which serves both to support the unit and to provide electrical insulation from the test specimen. The gage is bonded rigidly to the specimen by an adhesive, in such a manner as to transmit the strain from the specimen to the gage (Figure 3). In this configuration, the device commonly is called a "bonded" strain gage. An unbonded strain gage could involve wires stretched between supports on two components that move relative to each other. The bonded type of strain gage has become more common.

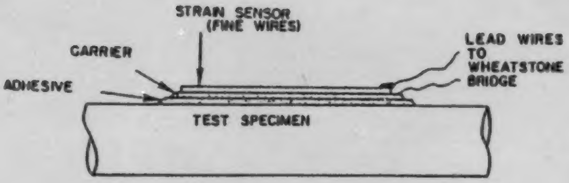


FIG. 3

A few of the metals used in metallic wire and foil gages are presented in Table 1, along with comments on useful temperature range and type of use. Static measurements refer to long-term measurement, in which the factors of high-strain sensitivity and good fatigue life become more important. Dynamic measurements refer to short-term measurements, in which the factors of high-strain sensitivity and good fatigue life become more important.

TABLE 1: METALLIC MATERIALS FOR STRAIN GAGES		
Metal	Temperature Range	Recommended Type of Measurement
Copper-nickel alloy (Constantan)	-100 to +460°F	Static
Nickel-chrome alloy (Nichrome V)	to 1200°F to 1800°F	Static Dynamic
Nickel-iron alloy (dynaloy)	Limited by carrier and adhesive	Dynamic
Nickel-chrome alloy (stabiloy)	to 600°F	Static
Platinum alloy (alloy 1200)	to 1200°F to 1500°F	Static Dynamic

For practical measurement of the relatively small resistance changes caused by strain, a Wheatstone bridge often is used, as illustrated in Figure 4. Unknown resistance of the gage is R_1; resistances R_2, R_3 and R_4 are known, with R_3 being a variable resistance. To find the value of the unknown resistance R_1, the variable resistor R_3 is adjusted until the galvanometer G registers no current flow; that is, $I_1 = I_3$, and $I_2 = I_4$. Under this balance condition, the four resistances must satisfy Equation 6.

$$R_1 = \left(\frac{R_2}{R_4}\right) R_3 \qquad (6)$$

R_1 can be determined by Equation 6 immediately from the known values R_2, R_3, and R_4. Commercially-packaged bridge networks are available; variable resistance may be adjusted simply by the rotation of dials until the meter on the instrument indicates zero current flow.

In practice, the bridge circuit may be set up as shown in Figure 5. A dummy gage is mounted on an unstrained sample of the same material that is being measured. The active gage is mounted on the strained material. This configuration compensates for changes in temperature, which affect both the active gage and the dummy gage identically.

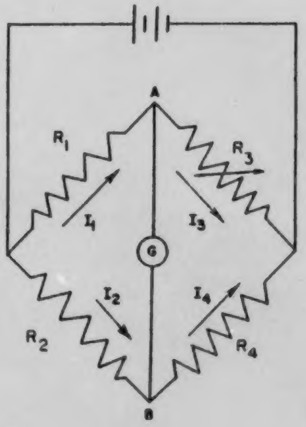


FIG. 4

Strain gages often are used in industry for measuring dimensional changes in specimens, as they offer the advantages of an easily-measurable electrical output, ease of installation and operation, and low cost. In addition to their direct use for measuring dimensional changes, they are utilized to determine the cause of strain.

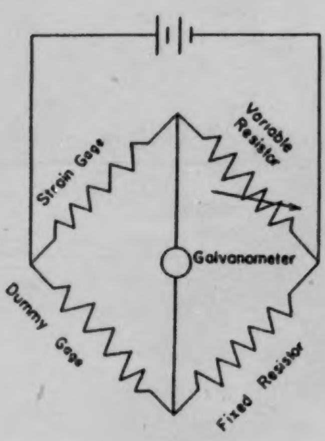


FIG. 5

SUMMARY

The strain gage is a transducer device used in the measurement of dimensional stress changes in a surface. The gage component (wire, foil, or semiconductor material) changes proportionally in resistance as strain changes upon the surface to which the gage is attached. This resistance is measured to determine the strain on the surface.

NICKEL WIRE RESISTANCE CHANGE

MATERIALS

Nickel wire, diameter 0.5 mm x length 36 in.
Spring scale.
Wheatstone bridge. (Refer to Step 1.)
Heavy immovable object for mounting.
Micrometer, 0-1 in.

PROCEDURE

In this experiment, the student will measure change in resistance of a nickel wire while it is being subjected to a tensile stress.

1. Set up apparatus as shown in Figure 6. Procedures assume that a commercial Wheatstone bridge is used, but an improvised bridge can be contructed with known resistors and a galvanometer, as shown in Figure 4. Attach one end of nickel wire to a heavy immovable object. Attach spring scale to other end. Measure initial unstrained resistance of wire with bridge; enter in Data Table 1.

2. Apply a force with spring scale; measure resistance again. Enter values in Data Table 1.

3. Repeat step 2 for several different values of applied force on spring scale, entering values in Data Table 1.

4. Measure diameter of wire with micrometer; calculate cross-sectional area. Check to see whether or not changes in radius with load are large enough to be taken into account.

5. For each value of applied force, calculate strain. (Remember that strain equals force per unit area divided by modulus of elasticity; for nickel, the modulus of elasticity is 3×10^7 pounds per square inch.) Enter values in Data Table 1.

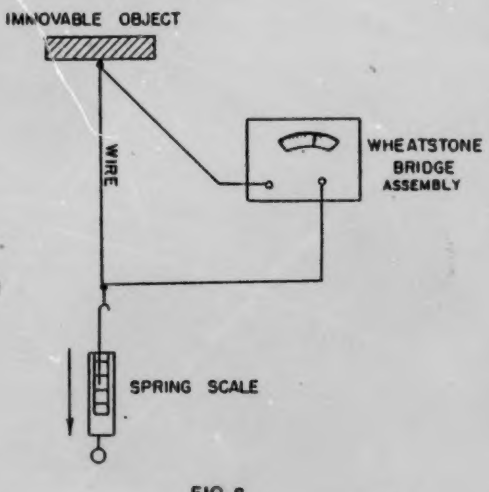


FIG. 6

6. What would be the gage factor of this wire if it were used as a strain gage?

METAL BAR STRAIN

MATERIALS

Spring scale.
Wheatstone bridge (as in previous experiment, step 1).
Metal bar (size-round 1/2 in diameter; square 1/4 in x 1/4 in x 48 in long).
Commercial bonded strain gage (model A-15X from BLH Electronics or equal).
Adhesive (Eastman 910 or equal).
Clamp.
Electrical lead wires and connectors, as needed.
Transparent pressure-sensitive tape, as needed.
Tissue, as needed.
Soldering iron and resin-core solder, as needed.

PROCEDURE

In this experiment, the student will use a commercial strain gage to measure strain in a metal bar.

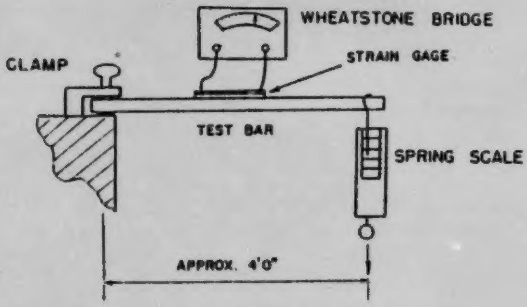


FIG.7

1. Set up apparatus as shown in Figure 7. Clamp one end of metal bar rigidly with a clamp mounted on a heavy immovable object.

2. Cement strain gage to top of bar by following instructions provided by manufacturer. If no instructions are supplied, use following procedures:

   Pick up gage with a piece of pressure-sensitive transparent tape. Spread a thin layer of adhesive on back of gage. Align gage accurately over area to which it will be attached; remember that once gage touches surface, to move it again probably will not be possible. Apply one end of tape to within about 1/8 in of gage end. Then wipe down tape and gage with a steady, progressive pressure, smoothing down with tissue so that cement does not touch fingers. Wait one minute; peel off tape slowly. Attach lead wires by soldering to lead-wire pads, if lead wires were not attached originally.

3. Connect Wheatstone bridge and attach spring scale.

4. Measure initial resisance with zero force on scale.

5. Measure resistance with a force on the scale. Calculate change in resistance. Enter values in Data Table 2.

6. Repeat step 5 for several increments of force on the scale; enter values in Data Table 2.

7. For each value of resistance change, calculate strain. Use manufacturer's stated value of gage factor.

8. How does the strain gage used in this experiment operate?

DATA TABLE 1

Scale Reading (Pounds)	Strain	Resistance (ohms)

DATA TABLE 2		
Scale Reading (Pounds)	Change in Resistance (Ohms)	Strain

SELF CHECK

1. Briefly describe strain gage operation.
2. Define gage factor for a strain gage. State ideal value of gage factor, and list at least one typical real value.
3. List three types of materials used in strain gages. Name at least one specific metal used.
4. A strain gage has an initial resistance of 400 Ω. Under a strain of 10^{-3}, resistance increases to 401 Ω. What is gage factor?

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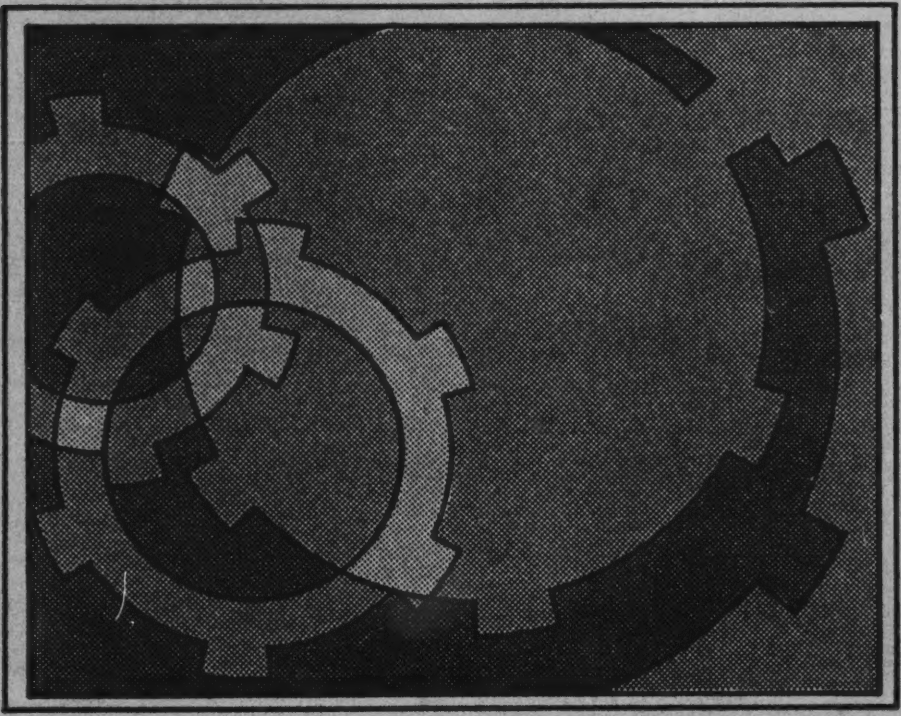
UNIFIED TECHNICAL CONCEPTS

MODULE 10 M 2

ACCELEROMETERS



MECHANICAL APPLICATION OF TRANSDUCERS

Technical Education Research Center-Southwest

TERC-SW

INTRODUCTION

The piezoelectric accelerometer contains certain crystals that exhibit surface charges when subjected to mechanical stress. The magnitude of the charge is proportional to the stress. The accelerometer transduces this mechanical stress energy into the electrical charge or voltage measured to determine acceteration.

This module investigates the construction and operation of the piezoelectric accelerometer. In the laboratory, the student will use an accelerometer to measure a variety of accelerations.

PREREQUISITES

Student should have completed Module 10-0, "Transducers."

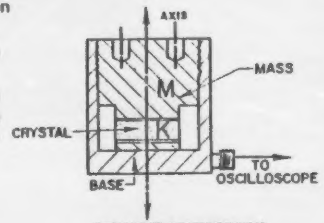
OBJECTIVES

Upon completion of this module, the student should be able to:

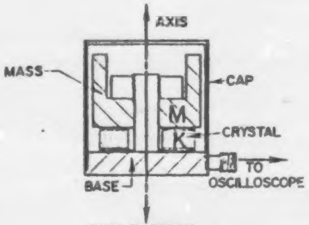
- Sketch and label the five major components of a single-ended compression accelerometer, including the critical axis; and describe in a sentence or two how it works.
- Sketch and label the three major components of a shear design accelerometer, its critical axis; and give a one- or two-sentence description of how it works.
- Sketch the voltage equivalent circuit of an accelerometer; and label the signal source, capacitance, and resistance.
- Name a type of accelerometer measuring device, and describe in one or two sentences its key characteristics.
- Given two of these three values, solve for the unknown quantity: acceleration, peak voltage, and sensitivity.

DISCUSSION

Figure I shows the components of a straight-compression and of a single-ended compression accelerometer. In each case, K is a piezoelectric crystal, and M is a mass held in contact with the crystal. A compression is maintained on the crystal at all times to increase the sensitivity of the accelerometer. When the device experiences an acceleration along the axis shown in the the figure, the pressure exerted on the crystal K by mass M changes. This pressure, in turn, changes the magnitude of the surface charge on the crystal. Electrodes on the crystal surface are connected to an electrical output to provide a means of measuring either the charge or the voltage produced.



STRAIGHT COMPRESSION



SINGLE-ENDED COMPRESSION

FIG. 1

While the straight-compression design is the simplest, it is seldom used in modern accelerometers. The single-ended compression design is the most common. It provides both electrical and mechanical isolation of the accelerometer from the case that encloses it. The cap of this design is a metal can welded to the accelerometer base; it seals the unit, but does not come into direct contact with the working parts of the accelerometer.

Figure 2 shows a shear-design accelerometer. The crystal is a cylinder bonded to a hollow shaft. A concentric cylindrical mass is bonded to the crystal, and the entire assembly is enclosed. An acceleration along the axis shown in the figure results in a shear force within the crystal. The electrodes are located on the inner and outer walls of the cylindrical crystal, and are connected to an electrical output.

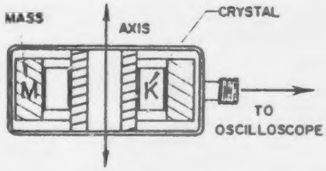


FIG. 2

Shear accelerometers can be built with extremely small dimensions and can be mounted by the passing of a machine screw through the central hole. Most microminiature accelerometers are of this design.

Measurement of the charge collected on the electrodes of the crystal is the most accurate measurement of acceleration. Because such measurement is both difficult and expensive, however, voltage measurements usually are made. Figure 3 shows the voltage equivalent circuit of an accelerometer and its associated voltage-measuring device. C_p is the capacitance of the accelerometer electrodes, and C_t is the capacitance of the cable used to connect the accelerometer to the measuring device. R_L is the input impedance of the voltage-measuring device (a vacuum-tube voltmeter, called a VTVM, or an oscilloscope). The charge generated by the crystal is q. For the best response, $C_p + C_t$ should be as small as possible, and R_L should be as large as possible.

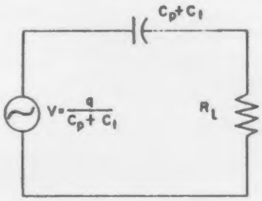


FIG. 3

Accelerometers usually are supplied with low-capacitance cables of known capacitance. The voltage sensitivity supplied by the manufacturer is based upon the use of these cables. The accelerometer will not be calibrated correctly if other cables are used.

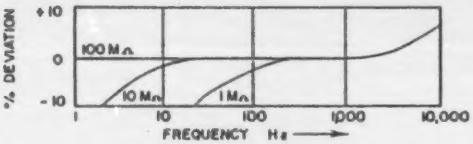


FIG. 4

Figure 4 shows the typical percentage of deviation from the calibrated voltage sensitivity of an accelerometer for three values of load resistance. This figure indicates that good low-frequency performance requires the use of a voltage-measuring device having a very high input impendance. Thus, an oscilloscope is the most common measurement device used.

Equation 1 is used to determine the acceleration measured by an accelerometer and oscilloscope combination.

$$a = \frac{V}{s} \qquad (1)$$

where

a = acceleration.
V = peak voltage in mV.
g = acceleration due to gravity.
s = sensitivity in $\frac{mV}{g}$.

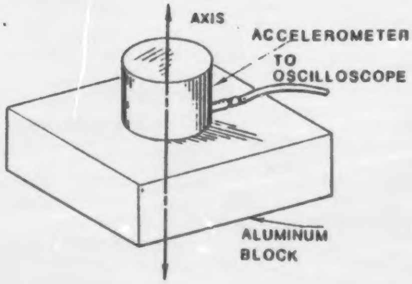


FIG. 5

The sensitivity usually is given in millivolts per g with a specified external capacitance (that of the connecting cable provided), and the resulting acceleration is measured in number of g's. Example A shows the use of Equation 1 in solving a problem.

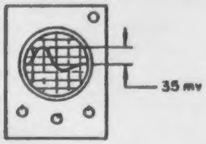
In practical applications, accelerometers must be firmly attached to the component whose acceleration is to be measured. If the accelerometer cannot be bolted directly to the component, it may be secured to a metal block held in contact with the component (Figure 5).

Recall from Figures 1 and 2 that accelerometers measure accelerations along one axis only. When mounted as shown in Figure 5, the accelerometer will respond only to those acceleration components that lie along its axis. Accelerations perpendicular to this axis cannot be seen by the device; therefore, the accelerometer can be used to measure both the magnitude and direction of accelerations.

EXAMPLE A: CALCULATION OF ACCELERATION USING ACCELERATION READINGS

Given: An accelerometer with a sensitivity of 16 mV/g was used to produce the oscilloscope trace shown in the below drawing.

Find: The acceleration.



Solution:

$$a = \frac{V}{S}$$

$$= 35 \text{ mV} \div 16 \frac{\text{mV}}{g}$$

$$a = 2.19 \text{ g}$$

The acceleration was 2.19 times the acceleration of gravity or $2.19 \times 32.2 \text{ ft/s}^2 = 70.5 \text{ ft/s}^2$.

SUMMARY

The piezoelectric accelerometer is a transducer that operates as follows: (1) Mechanical pressure, or stress, is applied to the accelerometer crystals during acceleration. (2) This stress energy is transduced by the crystals into an electrical charge proportional to the stress. (3) The electrical charge or voltage is measured to obtain the amount of acceleration. Accelerometers can measure the magnitude and the direction of accelerations.

ACCELEROMETER MEASUREMENTS

MATERIALS

Accelerometer (Endevco model 2215E or equal).
Oscilloscope with 0.005 V/cm sensitivity.
Aluminum block approximately 2" x 2" x 1" drilled and tapped to accept accelerometer stud.
Centimeter scale.
Several sources of mechanical vibration, such as drill press, electric shaver, electric fan, saw, etc.

PROCEDURE

1. Attach accelerometer securely to aluminum block, as shown in Figure 5. Use cable provided to connect accelerometer to input of oscilloscope.

2. Turn on oscilloscope, and obtain a stable trace on the scope display. Voltage sensitivity of the oscilloscope should be set for 0.005 V/cm. Note that this setting and time base of oscilloscope must be changed to the appropriate settings throughout the experiment to give the best display. Settings necessary will vary with sources of vibration used.

3. Place mounted accelerometer on a table, and tap block lightly with one finger while observing oscilloscope. Display shows variations in acceleration experienced by accelerometer. Tap block lightly with a pencil or screwdriver, and observe resulting vibrations.

4. Hold accelerometer 2 cm above table top, with its axis vertical. Drop accelerometer while observing oscilloscope. Record in Data Table amplitude and frequency of resulting accelerations.

5. Repeat above procedure with accelerometer axis horizontally.

6. Place accelerometer on floor, with its axis vertical. Have another student jump as high as possible and land a few feet from accelerometer. Record results from oscilloscope.

7. Repeat step 5 with accelerometer axis horizontal.

8. Place accelerometer mounting block in contact with a source

of mechanical vibration. Observe and record results.

9. Use same source of mechanical vibration, but rotate accelerometer axis by 90°. Record results.

10. Repeat steps 7 and 8 for another source of mechanical vibration.

11. Complete the Data Table.

12. If the oscilloscope did not display a voltage during some of the tests, or if it displayed a very small voltage, why?

DATA TABLE

Source of Acceleration	Accelerometer Axis	Peak Voltage (mV)	Sensitivity (mV/g)	Acceleration (a)	Frequency Hz
2 cm vertical drop	vertical				
2 cm vertical drop	horizontal				
floor vibration	vertical				
floor vibration	horizontal				
mechanical vibration	any angle				
mechanical vibration	rotate 90°				

SELF CHECK

1. Sketch and label the five major components of a single-ended compression accelerometer, including the critical axis; and describe in a sentence or two how it works.

2. Sketch and label the three major components of a shear-design accelerometer, its critical axis; and give a one- or two-sentence description of how it works.

3. Sketch the voltage-equivalent circuit of an accelerometer; and label the signal source, capacitance, and resistance.

4. Name a type of accelerometer measuring device, and describe in one or two sentences its key characteristics.

5. An accelerometer with a sensitivity of 15 mV/g produces a voltage of 0.55 volts when in contact with an engine. What is the acceleration?

6. An accelerometer with a sensitivity of 12 mV/g is used to measure an acceleration of 2.6 g. What voltage is produced?

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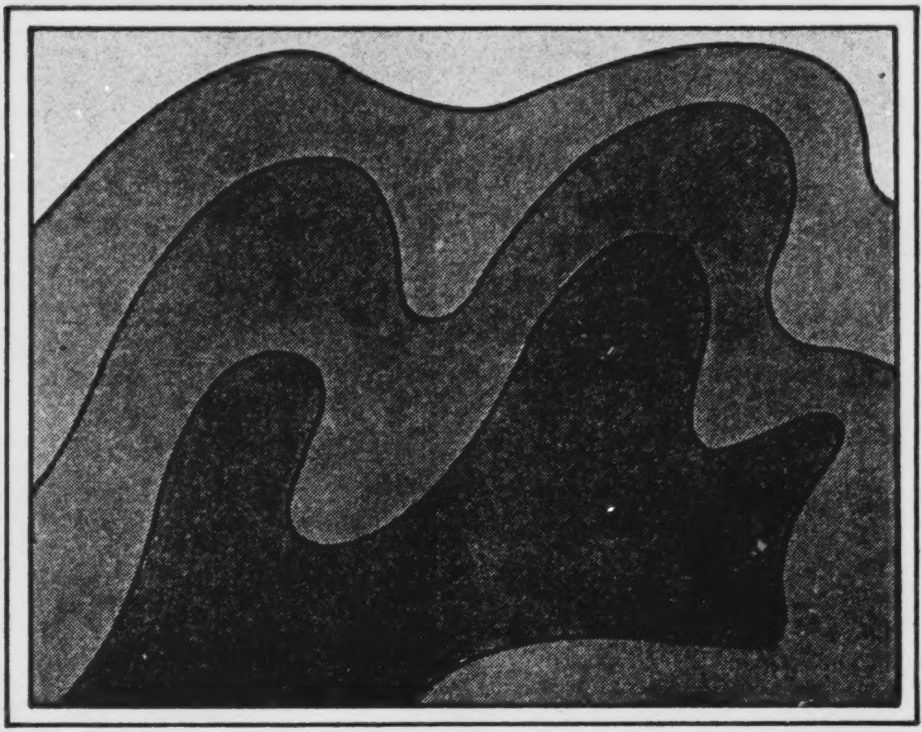
UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 10 F 1

BOURDON TUBES



FLUID APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest

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NOV 1979

INTRODUCTION

The bourdon tube is a mechanical transducer used to measure pressure. The measurement of pressure is one of the most important functions in the field of measurement and control, not only because of the pressure measurement itself, but also because such measurement indicates other important parameters, such as temperature, liquid level, and flow. The bourdon tube pressure element transforms fluid energy or motion into detectable pressure changes on a readout device.

This module discusses the design and operation of the bourdon tube and, briefly, of the bellows and the diaphragm pressure transducers. In the laboratory, the student will operate and calibrate a bourdon tube.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Compare the operation and application of five types of pressure elements used as transducers.
- Given a specific application, identify the appropriate pressure element.
- Given the appropriate equipment, operate and calibrate a bourdon tube.

DISCUSSION

The bourdon tube is a general type of pressure element, consisting of the simple "C" tube, helical, and spiral elements (Figure 1). Bellows and diaphragms are not classified as bourdon tubes, but are widely used as pressure transducers. Regardless of the type of transducer used, the basic principle of operation is the same: pressure applied to the tube causes a movement interpreted as a pressure measurement. A bourdon tube obeys Hooke's law, which states that within elastic limits, the free end of a bourdon tube will move in proportion to the fluid pressure applied. Thus, fluid energy is transformed to the potential energy of a spring-like element used to determine pressure.

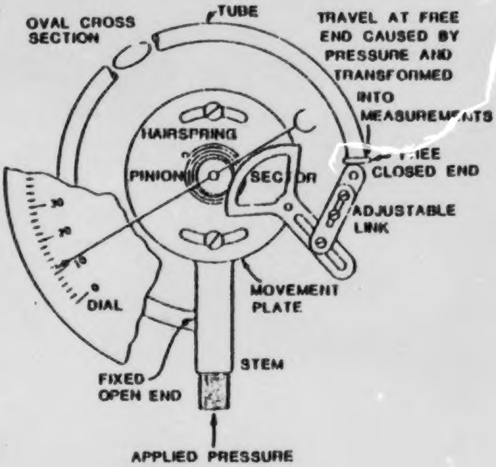
OVAL CROSS SECTION
TUBE
TRAVEL AT FREE END CAUSED BY PRESSURE AND TRANSFORMED INTO MEASUREMENTS
HAIRSPRING
PINION
SECTOR
FREE CLOSED END
ADJUSTABLE LINK
30
20
10
0
DIAL
MOVEMENT PLATE
STEM
FIXED OPEN END
APPLIED PRESSURE

FIG. 1

The bourdon C-tube shown in Figure 1 is the most common type of pressure element, the easiest to construct, and therefore, cheapest.

Pressure applied to the tube causes distortion in the shape of the device. Such distortion results in a small movement of the free end. This movement is rather small; so it is usually transformed and amplified by use of levers and gears to cause a rotation of a shaft. When a pointer is connected to the shaft, the shaft rotation causes the pointer to move along a graduated, calibrated scale. The relationship between pressure applied to the tube and movement of the tube depends upon tube construction and shape.

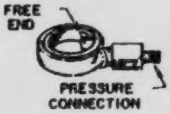
FREE END
PRESSURE CONNECTION

FIG. 2

Sprial (Figure 2) and helical (Figure 3) bourdon tubes operate on the same principle described above, but have the advantage of producing more travel of tip for a given applied pressure. The operation of a spiral element is the same as that of a "party favor," which tends to uncoil when pressure is applied to the device (Figure 4). The amount of uncoiling is proportional to the lung pressure applied; however, the spiral element does not uncoil completely like the party favor mentioned, because to do so would cause a distortion of the metal, and the element would return to its original shape. One end of the spiral is mounted rigidly to a frame; the movement at the free end is transmitted to a pointer, which, in turn, moves along a calibrated scale to indicate pressure. Table 1 gives the pressure range that can be measured with different spiral-element materials.

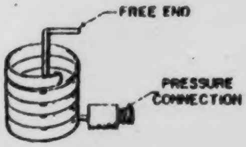
FREE END
PRESSURE CONNECTION

FIG. 3

The helical element (Figure 3), instead of having coils in the same plane, is manufactured so that the coils are the same diameter and extend a vertical distance of one to five inches. The physical appearance resembles a coil spring.

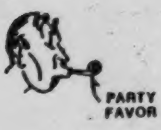

FIG. 4

Helical elements normally are made of thicker material and, consequently, can be used for higher pressure applications. Like the spiral, helical elements allow more movement at the tip than the C-tube and sometimes are used to drive an indicating device directly without the use of movement amplification by a link-and-lever system. Table 2 gives the pressure range for different helical element materials.

TABLE 1 : PRESSURE RANGE OF SPIRAL ELEMENTS	
Bronze	0-10 to 0-200 psi
Beryllium-Copper	0-10 to 0-200 psi
Ni-Span C Alloy	0-10 to 0-200 psi
Type 316 SS	0-12 to 0-200 psi

TABLE 2 : PRESSURE RANGE OF HELICAL ELEMENTS	
Bronze	0-201 to 0-400 psi
Beryllium-Copper	0-201 to 0-6000 psi
Ni-Span C Alloy	0-201 to 0-6000 psi
Type 316 SS	0-201 to 0-6000 psi
Heavy Duty Helical Elements:	Pressure Range
Type 316 SS	0-75 to 0-30,000 psi
	0-40,000 to 0-60,000 psi

All pressure elements operate on the energy transformation principle. Pressure applied to the element causes a movement. Since pressure applied through a distance represents fluid energy (recall, $\Delta W = p\Delta V$), the fluid energy is transformed into the mechanical energy of the indicating system. In this case, the mechanical energy is contained as potential energy in the deformed spiral or helix; therefore, the distortion is a direct measure of the pressure. Depending upon the type of material and physical construction of the element, it will offer an opposition to movement. For a given pressure, the opposition to movement and the pressure on the element are in a state of equilibrium. When the pressure changes, the element will move until this movement causes the element to build up an opposition to this movement. The operation is similar to a force applied to a spring and the opposition to movement by the spring. The spring moves until its force is equal to the applied force.

The force exerted by a pressure element is proportional to the applied pressure and the area of the element. A large-area pressure element is required for the measurement of extremely small pressures. For small pressure application, the diaphragm element is used (Figure 5). This type of energy transformer will produce a considerable amount of movement when a small pressure is applied. Presssure gages and transmitters using a diaphragm as an element can measure pressures as small as 0.30 pounds per square inch. Table 3 gives the pressure range for different diaphragm elements.

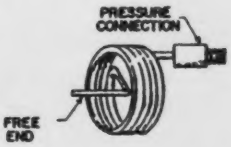

FIG. 5

TABLE 3 : PRESSURE RANGE OF DIAPHRAGM ELEMENTS	
3-inch, Cu-Ni-Mn	0-8 to 0-40 inches of water
2-inch, Cu-Ni-Mn	0-20 inches of water to 0-5 psi

The relationship between movement and pressure should be a direct proportionality for any type of pressure element. Ideally, equal increments of pressure should produce equal increments of movement at all points throughout the pressure range of the device. The bellows element is one of the most accurate pressure transducers because movement is more nearly proportional to pressure (Figures 6 and 7). A bellows element in operation resembles a small accordion. When pressure is applied to a bellows element, the side of the element expands; and when the pressure is removed, the side collapses to the original size. Table 4 gives the pressure range for different bellows-element materials.

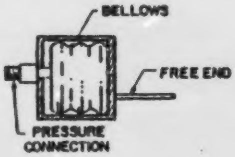

FIG. 6

TABLE 4 : PRESSURE RANGE OF BELLOWS ELEMENTS

Brass	0-100 inches of water to 0-25 psi
Type 316 SS	0-4.5 to 0-29 psi

Pressure elements are used in pressure gages and transmitters, providing the driving force to operate pressure switches. Common applications of pressure switches include those used to start and stop water pumps and air compressors. Most pressure switches use a diaphragm or bellows, because a pressure applied to the large area of these elements can produce forces sufficient to operate the switch.

The switch (Figure 7) is in the de-energized position. When the pressure decreases, the bellows will contract, causing the electrical contact to close and starting the motor to drive a pump. When the pump increases the pressure, the switch will again open, stopping the pump.

The adjustable spring is set to establish the best operating point.

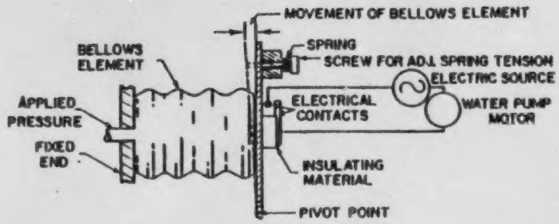
MOVEMENT OF BELLOWS ELEMENT
SPRING
SCREW FOR ADJ. SPRING TENSION
ELECTRIC SOURCE
BELLOWS ELEMENT
APPLIED PRESSURE
FIXED END
ELECTRICAL CONTACTS
WATER PUMP MOTOR
INSULATING MATERIAL
PIVOT POINT

FIG. 7

SUMMARY

The bourdon tube is a transducer that transforms a pressure change into a needle-indicator deflection. The elastic element is a tube fixed at one end (open to accept applied pressure) but free at the other end (closed to allow displacement under the deforming action of the pressure difference across the tube walls). The most common design consists of a tube having an oval cross section and bent in a circular arc which straightens out slightly under pressure. By an almost frictionless linkage, the free end of the tube rotates a pointer over a calibrated scale to give a pressure indication.

LABORATORY

OPERATION AND CALIBRATION OF A BOURDON TUBE

MATERIALS

0-10 lb (4 1/2" diameter) pressure gage using a C-tube as an energy transformer.

A 30-lb pressure source: a small, portable air compressor can be used. Caution: Do not use a higher air pressure than 30 lb/square inch. Higher pressures can be dangerous. (Note: Many labs already are equipped with pressurized air ports.)

A "U" tube mercury manometer. (Caution: Care should be taken when working with mercury to avoid contact with skin and eyes. Mercury also is corrosive to gold jewelry.)

Variable pressure regulator.

Assorted pipe fittings and rubber hose.

All equipment needed for the exercises in this module is available from the Curtis Scientific Company, 4220 Jefferson Avenue, Houston, Texas 77001.

The manometer used in this module can be replaced with a previously-calibrated pressure gage. The standard practice, however, is to use a mercury manometer as a readable and accurate standard for calibration purposes.

PROCEDURE

The purpose of this procedure is to allow the student to observe the operation of a pressure element and to check the calibration of a pressure instrument, using a pressure element as an energy transformer.

1. Connect the equipment as shown in Figure 8.
2. Remove the glass, pointer, and dial from the pressure gage. This removal should expose the Bourdon C-tube. Observe the mechanical linkage by which the movement at the free end of the C-tube is converted to a rotary motion at the pointer hub.
3. In order to observe the operation of the C-tube during the test, do not replace the dial.

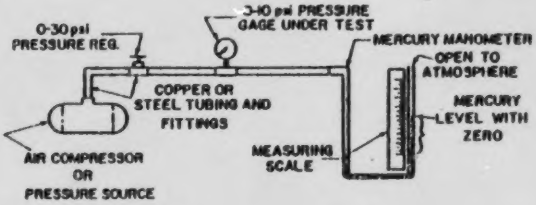
3-10 psi PRESSURE
GAGE UNDER TEST
0-30 psi
PRESSURE REG.
MERCURY MANOMETER
OPEN TO
ATMOSPHERE
COPPER OR
STEEL TUBING AND
FITTINGS
MERCURY
LEVEL WITH
ZERO
MEASURING
SCALE
AIR COMPRESSOR
OR
PRESSURE SOURCE

FIG. 8

With a soft lead pencil, mark the case of the gage in 10% increments corresponding to the dial markings.

4. With no pressure applied to the gage, replace the pointer on the zero pound mark.

5. Carefully adjust the pressure regulator until the manometer reads a pressure equal to 1 lb/square inch. (Note: To convert the reading on the mercury manometer to pounds per square inch, use the following conversion: 1 inch mercury = 0.4912 lb/in^2.) In Data Table, record the pressure reading on the pressure gage.

6. Repeat settings on the pressure regulator in increments of 10%. Record.

7. Calculate and record % error as indicated in Data Table.

DATA TABLE

% Reading on Gage	% Reading on Manometer	Error (%)*
0		
10		
20		
30		
40		
50		
60		
70		
80		
90		
100		

*Note: To calculate % error —

$$\% \text{ error} = \frac{\text{manometer reading} - \text{gage reading}}{\text{manometer reading}} (100)$$

8. Make a plot of the readings from the Data Table, and determine if the gage is accurately measuring the pressure. The graph should be similar to the one shown in Figure 9, in which line A represents good calibrations. When all points

fall on a straight line 45° to both axes, the gage is calibrated properly.

Lines B represent zero point error — either high or low. The line is parallel to line A, but is offset by some constant amount.

Lines C represent an error caused by too much or too little span adjustment. The error increases as the reading progresses from the zero point.

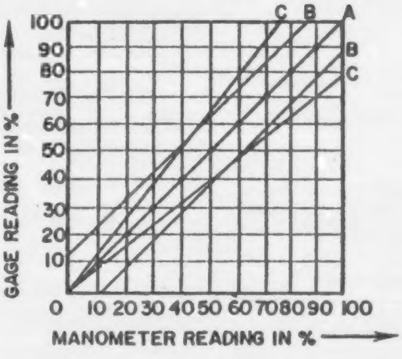

FIG. 9

If the calibration curve is other than line A, the pressure gage is not properly calibrated. In this case, proper calibration adjustment should be made. The adjustments are necessary to cause the movement of the pointer to correspond correctly to the movement of the C-tube or pressure transducer (Figure 9). The relationship of pressure and movement of the pressure element cannot be changed. This relationship is established by physical characteristics, such as the thickness and material type of element, when it is constructed. Movement of the pointer must correspond to the tip travel of the pressure element.

A zero adjustment can be made by removing the pointer from the shaft attached to the pinion gear and by positioning the pointer to the 0 location on the scale. By loosening screw "s" and sliding the lever, the mechanical advantage of the device can be changed. This is a span adjustment.

9. Calibration procedure. (See Figure 10.)

   a. With zero pressure applied to the pressure gage, position the pointer to zero on the scale.

   b. Apply 100% pressure — 10 psi for a 10 psi gage — and note the gage reading. If too high, move the span adjustment in such a manner as to reduce the mechanical advantage of the device. If too low, increase the mechanical advantage.

   c. Manipulate the pressure regulator until zero pressure is applied to the gage. Position the pointer until it corresponds to the zero on the scale.

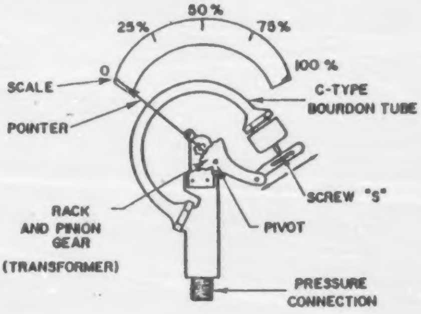

FIG. 10

d. Repeat Steps b and c until no further adjustment is necessary.

If the gage is new, the calibration should be good. To gain practice in calibration and to observe operation of the C-tube, uncalibrate the gage by making a random adjustment to zero and span, and go through the calibration procedures.

SELF CHECK

1. Discuss the operation and application of the following types of pressure elements used as transducers:

    Bourdon C-tube.
    Bourdon spiral tube.
    Bourdon helical tube.
    Diaphragm element.
    Bellows element.

2. Compare the operation and application of the Bourdon helical tube to that of the bellows element.

3. A pressure system operates at 4500 psi with a gas that corrodes type 316 SS tube. What types of helical element material are available to the system designed?

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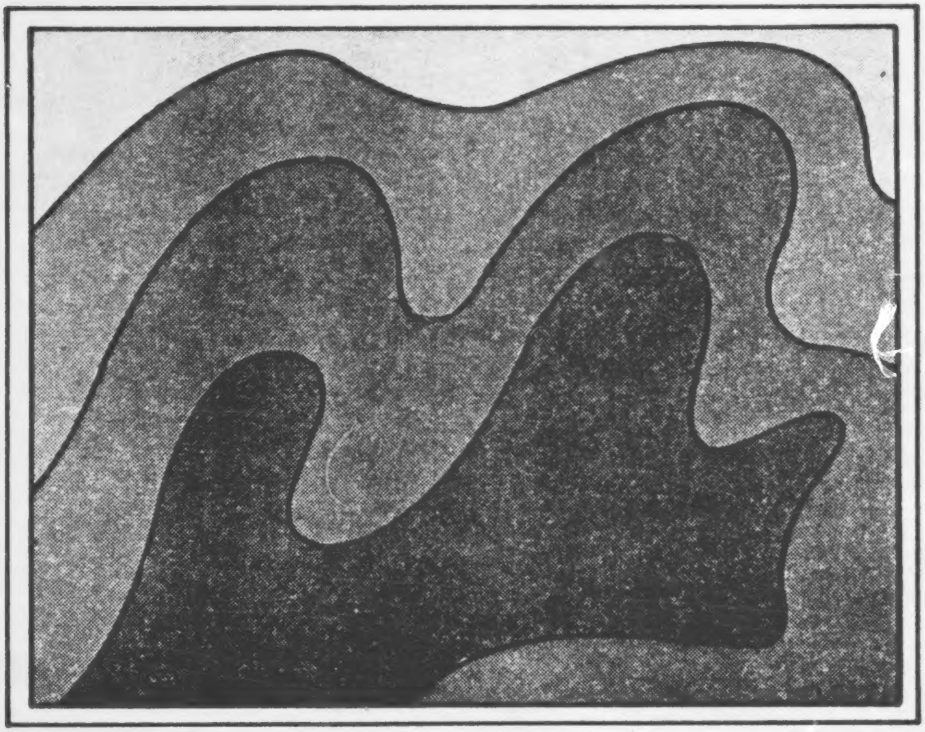
UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 10 F 2

ANEROID BAROMETERS



FLUID APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest

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INTRODUCTION

An aneroid barometer is an energy transformer that accepts input energy from pressure of gas surrounding it and transforms it into potential energy of a spring. A pointer or other display device indicates amount of energy stored in the spring. The instrument is usually calibrated in units of pressure.

In this module, construction and applications of an aneroid barometer and other instruments employing the same principles will be investigated. In the laboratory, the student will measure a variety of pressures with an aneroid barometer and express each pressure in several standard pressure units.

PREREQUISITES

The student should have completed Concept Module 10-0, "Transducers," and Application Module 1F2, "Density, Buoyancy and Specific Gravity."

OBJECTIVES

To complete this module, the student should be able to:

- Diagram an aneroid barometer with its five basic elements.
- In a brief paragraph, discuss how the aneroid barometer functions as an energy transformer.
- Define the following terms in one or two sentences:
    - Aneroid.
    - Barograph.
    - Altimeter.
    - Bar.
    - Millibar.
    - mm Hg.
    - in Hg.
    - Torr.
- Convert pressure readings, given in any one of the follow-

ing units, to each of the other units:
  mm Hg.
  in Hg.
  millibar.
  Torr.
  lb/in^2.

- Using an aneroid barometer and necessary equipment, measure at least four different pressures and convert readings to any of the scales in Objective 4.

DISCUSSION

The mercury barometer described in Module F2, "Density, Buoyancy and Specific Gravity," is a device for determining atmospheric pressure by measuring height of a column of mercury. Mercury barometers are highly accurate but are delicate, large and not easily portable. Aneroid barometers are employed in applications where small size, light weight and portability are desirable. Aneroid means "not using a liquid." Thus aneroid barometers are energy transformers, specifically pressure-measuring devices, that do not employ a column of liquid to determine pressure.

Figure 1 shows basic elements of a simple aneroid barometer. The aneroid capsule is a sealed metal container from which much of the air has been evacuated, so that internal pressure is near zero. Sides and ends of the container are corrugated to make it flexible. The spring is arranged to provide an upward force on the top of the aneroid capsule. A gear drive positions a pointer on a scale to indicate spring position, which in turn indicates a gas pressure.

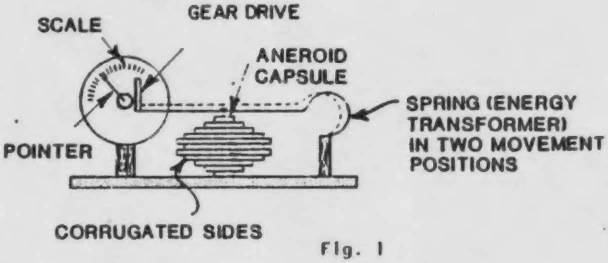

Fig. 1

The aneroid barometer is best explained as an energy transformer and storage device. In a vacuum, no outside pressure is present on the aneroid capsule and the spring holds its top at a maximum height. As gas pressure increases on the capsule, it is compressed and the spring is pulled downward. Energy expended on the aneroid capsule by the atmosphere is the product of the compression force and the distance through which the top of the capsule moves. This energy is transformed into potential energy stored in the spring. The spring is connected to a needle that indicates amount of energy stored on a scale. In an aneroid barometer, this scale is calibrated in units of pressure.

COMMON UNITS OF PRESSURE

There are three common units of pressure commonly employed with aneroid barometers.

INCHES OF MERCURY

One "inch of mercury" is pressure necessary to maintain a column of mercury one inch high in a mercury barometer.

MILLIMETERS OF MERCURY

One "millimeter of mercury" is pressure necessary to maintain a column of mercury one millimeter high in a mercury barometer. Torr is another name for this unit, in honor of Torricelli, an early pioneer in vacuum work.

MILLIBAR

A millibar is one one-thousandth of a bar or 10^3 dynes/cm². This is the only true pressure unit commonly used (that is, the pressure unit is expressed directly in units of force/area).

Table I gives average atmospheric pressure at sea level in each of these units.

TABLE I: ATMOSPHERIC PRESSURE AT SEA LEVEL

lb/in²	in of Hg*	mm of Hg**	Torr	mb***
14.7	29.92	760	760	1013

*Inches of mercury. **Millimeters of mercury. ***Millibar.

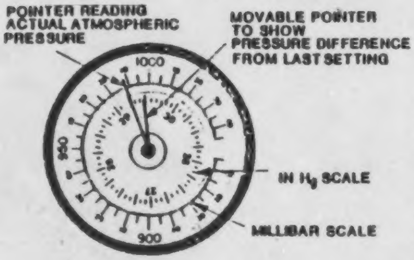
POINTER READING ACTUAL ATMOSPHERIC PRESSURE
MOVABLE POINTER TO SHOW PRESSURE DIFFERENCE FROM LAST SETTING
1000
950
900
IN Hg SCALE
MILLIBAR SCALE

Fig. 2

This table may be used for conversions from one unit to another, as shown in Example A.

Figure 2 shows the scale of a typical aneroid barometer that may be mounted on a wall. This instrument has scales calibrated in millibars and inches of mercury. It is useful for a pressure range of 25 in Hg to 32 in Hg. An additional pointer is provided that may be set manually to agree with the pressure-indicating needle. At a later time, difference in the two pointers will indicate whether the atmospheric pressure is rising or falling.

Figure 3 shows a barograph. In this instrument, a pen makes a permanent record of atmospheric pressure on a revolving chart marked in hours and days.

Both of these instruments are used in studying changes in barometric pressure and are used in forecasting weather. In general, higher pressures mean fair weather and lower pressures mean rainy or stormy weather.

EXAMPLE A: PRESSURE UNIT CONVERSION

Given: A barometric pressure of 26 in of Hg.

Find: Equivalent in mm of Hg and mb.

Solution:

(a) If 29.92 in Hg = 760 mm Hg

$$\text{then } 26 \text{ in Hg} = 26.0 \text{ in Hg} \times \frac{760 \text{ mm Hg}}{29.92 \text{ in Hg}}$$

$$= 660 \text{ mm Hg.}$$

(b) If 29.92 in Hg = 1013 mb

$$\text{then } 26 \text{ in Hg} = 26 \text{ in Hg} \times \frac{1013 \text{ mb}}{29.92 \text{ in hg}}$$

$$= 880 \text{ mb.}$$

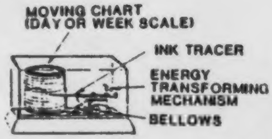
MOVING CHART (DAY OR WEEK SCALE)
INK TRACER
ENERGY TRANSFORMING MECHANISM
BELLOWS

Fig. 3

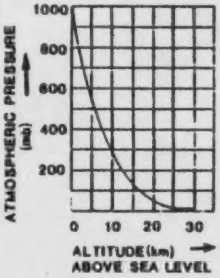

Fig. 4

As shown in Figure 4, atmospheric pressure decreases as altidude increases. Thus altitude above sea level may be calculated if air pressure is known. Figure 5 shows an altimeter, which makes use of this pressure transformation to measure altitude. The more complex gear drive of this instrument positions three pointers, which allows an aircraft pilot to read altitude directly from the scale. The barosetting knob is used to set atmospheric pressure at some known point on the ground. The altimeter is then calibrated to display altitude above that point.

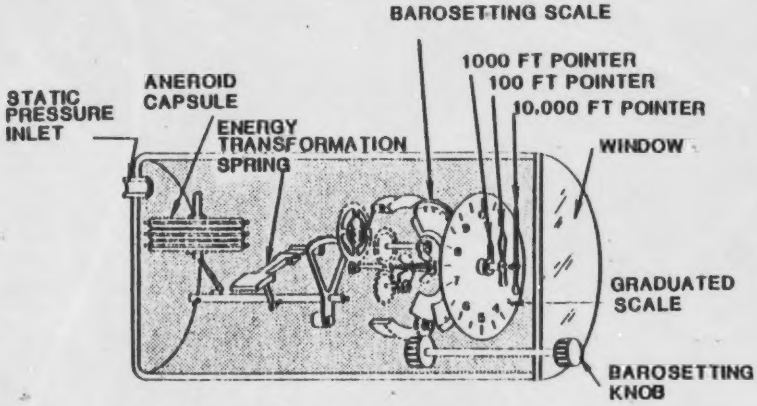
BAROSETTING SCALE
1000 FT POINTER
100 FT POINTER
10,000 FT POINTER
STATIC PRESSURE INLET
ANEROID CAPSULE
ENERGY TRANSFORMATION SPRING
WINDOW
GRADUATED SCALE
BAROSETTING KNOB

Fig. 5

LABORATORY

MATERIALS

Aneroid barometer.
Vacuum base plate.
Bell jar.
Two inches of surgical tubing to fit base plate outlet.
Vacuum grease.

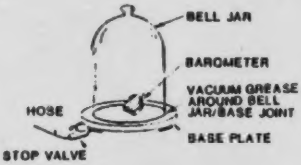

Fig. 6

PROCEDURE

1. Place barometer on base plate of bell jar (Figure 6). Apply a thin coat of vacuum grease around edge of bell jar and seat it over barometer. Connect tubing to base-plate outlet.
2. Record atmospheric pressure as indicated by barometer in column A of Data Table 1 (trial 1).
3. Blow gently into tubing to increase pressure inside bell jar. It may be necessary to press down on top of jar to prevent air leakage. Be careful not to exceed indicated pressure range of barometer. Pressure may be held steady at any desired value by closing stop valve. Record increased pressure in column A of Data Table 1 (trial 2).
4. Lower air pressure in bell jar by sucking air out through surgical tubing. Once again, be careful not to exceed indicated pressure range of barometer. Record decreased pressure in column A of Data Table 1 (trial 3).
5. Repeat steps 3 and 4 to obtain two additional pressure readings (trials 4 and 5).
6. Use conversion factors from Table 1 and convert column A data to units headed by columns B through E. Then complete Data Table 1 (columns B through E).

DATA TABLE 1

Trial	Column A in Hg	Column B mm Hg	Column C mb	Column D torr	Column E lb/in^2
1					
2					
3					
4					
5					

SELF CHECK

1. Diagram basic elements of an aneroid barometer.
2. Describe how an aneroid barometer functions as an energy transformer.
3. Define the following terms:
    - Aneroid.
    - Barograph.
    - Altimeter.
    - Bar.
    - Millibar.
    - mm Hg.
    - Torr.
    - in Hg.
4. Convert pressures given in Data Table 2 into the other pressure units and complete Data Table chart.

DATA TABLE 2

lb/in^2	in Hg	mm Hg	torr	mb
15.2				
	27.8			
		550		
			680	
				900

REFERENCES

Encyclopedia International, Vol. 2. New York: Grolier, Inc., 1969.

McGraw-Hill Encyclopedia of Science and Technology, Vol. 2. New York: McGraw-Hill, 1960.

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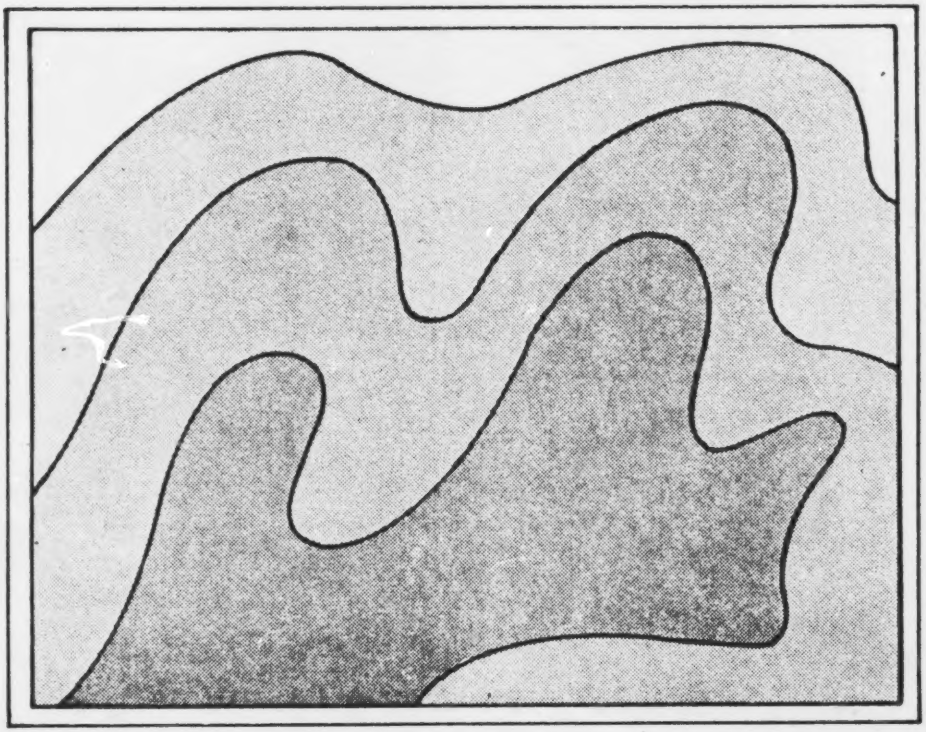
UNIFIED TECHNICAL CONCEPTS

MODULE 10 F 3

DIFFERENTIAL PRESSURE TRANSDUCERS



FLUID APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Measurement of pressure is a common transducer application for both industrial and residential uses. Of practical importance is the distinction between absolute and gage pressure measurements, which involve different reference pressure levels. Differential-pressure transducers are typically employed in measurement of liquid levels and fluid flow rates.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers."

OBJECTIVES

To complete this module, the student should be able to:

- Convert gage pressure to absolute pressure.
- Describe two types of differential-pressure transducers.
- Adjust and calibrate a differential-pressure transducer.
- Given a differential-pressure transducer, measure liquid level and fluid flow.

When barometric pressure is given as 760 mm of mercury or 14.7 psi, it is understood that this measurement is an absolute pressure, that is, referenced to zero mm of mercury or zero psi. This reference level would define a perfect vacuum. When one inflates a tire to 30 psi, on the other hand, the reference level is atmospheric pressure, or 14.7 psi. If atmospheric pressure should later change by 0.7 psi, this would represent a change in reference level. For example, if the reference level decreases by 0.7 psi and the same tire pressure is again measured with a tire gage, the gage would read 30.7 psi (30 + 0.7). The pressure of 30.7 psi is 0.7 psi higher than the initial pressure because the reference level was lowered by 0.7 psi. Absolute pressure inside the tire (compared to zero pressure) does not change, but measured pressure is different because the reference level changes.

Figure 1 illustrates two scales of pressure measurement. The measurement on scale A is referenced to absolute zero pressure (psia) or a vacuum. Scale B measurements are gage pressures (psig) and are referenced to atmospheric pressure, which is 14.7 pounds per square inch above zero absolute. It can be seen from the scale in Figure 1 that psia = psig + 14.7.

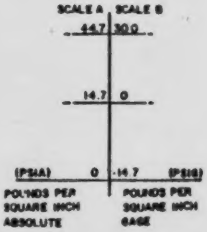


Fig. 1

Measurements on both scales are in effect differential measurements because, as mentioned earlier, psia is the difference between some measured pressure and absolute zero pressure, while psig represents a value that is measured as a difference between some pressure and atmospheric pressure. Elements that are used as transducers to measure pressure produce a movement proportional to difference in pressure between the inside and outside of the device.

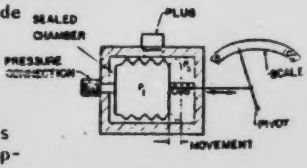


Fig. 2

When pressure is applied to a bellows (Figure 2), the pointer will move to the right. Movement will cease when a state of equilibrium exists between forces on the inside and outside of the bellows. Force on the inside of the bellows is caused by pressure applied to the bellows. What causes the opposing force on the outside of the bellows? A spring is commonly used, which helps establish pressure range of the bellows. Recall that force is the product of pressure and the area over which pressure is exerted. If pressure on the inside and outside changes by the same amount and in the same direction, there will be no resultant movement of the bellows and hence no change in indications.

Resultant force on the bellows can be shown by the following relationship:

$$F_1 = P_1A_1 \quad (1)$$

$$F_2 = P_2A_2 \quad (2)$$

where

F_1 = force on inside of bellows.
P_1 = pressure on inside of bellows.
A_1 = area of inside of bellows.
F_2 = force on outside of bellows.
P_2 = pressure on outside of bellows.
A_2 = area on outside of bellows.

By design of the bellows, $A_1 = A_2 = K$ and does not enter into the force relationship. Then:

$$F_1 = P_1K \quad (3)$$

and

$$F_2 = P_2K \quad (4)$$

By subtracting Equation 4 from Equation 3, we obtain:

$$F_1 - F_2 = (P_1 - P_2)K \quad (5)$$

From the above, it can be seen that difference in force that causes movement of the bellows is proportional to difference in pressure on each side of the pressure element.

For differential-pressure applications, diaphragms and bellows are most often used because of their ability to measure small differential pressure.

Construction of a differential-pressure transducer is such that pressure can be applied to both sides of the pressure element (Figure 3). One pressure will cause the indications to increase, while pressure applied to the other side of the element causes indication to decrease. The two ports through which the pressures are applied to the transducers are called the HIGH SIDE and LOW SIDE connections. Pressure applied to the HIGH SIDE connection causes the indication to increase, while pressure applied to the LOW SIDE causes a decrease in reading. Equal pressure applied to both connections causes no response from the instrument.

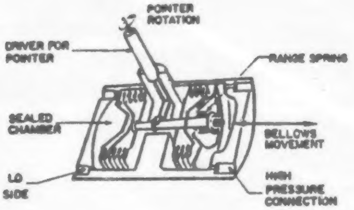

POINTER ROTATION
DRIVER FOR POINTER
RANGE SPRING
SEALED CHAMBER
BELLOWS MOVEMENT
LO SIDE
HIGH PRESSURE CONNECTION

Fig. 3

TWO DIFFERENTIAL-PRESSURE TRANSDUCER APPLICATIONS

LEVEL MEASUREMENT

Recall from Module 10F1 that liquid level can be inferred from a pressure measurement that is caused by a hydrostatic head. Remember that a hydrostatic head is the pressure that a column of liquid exerts on the bottom of its container. An application for liquid level measurement by hydrostatic head is shown in Figure 4.

Relationship between hydrostatic head and liquid height can be expressed by the formulas:

$$\text{Pressure} = 0.433 \text{ psi/ft} \times (\text{specific gravity of fluid}) \times (\text{ft of head}).$$

Therefore,

$$\text{Level}_{(\text{ft})} = \frac{\text{pressure}}{0.433 \times \text{specific gravity}}.$$

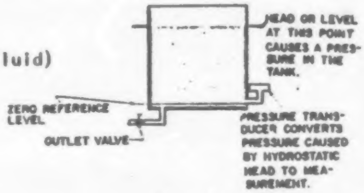

HEAD OR LEVEL AT THIS POINT CAUSES A PRESSURE IN THE TANK.
ZERO REFERENCE LEVEL
OUTLET VALVE
PRESSURE TRANSDUCER CONVERTS PRESSURE CAUSED BY HYDROSTATIC HEAD TO MEASUREMENT.

Fig. 4

This is an effective means of measuring level. Consider, however, the error caused by a change in pressure at the top of the tank. As with measurement of any variable, a response of the measuring device should be caused by a change in the measured variable. If the application of Figure 4 is to provide an accurate means of level measurement, it is necessary for pressure on the top of the liquid to remain at the same pressure as that on the outside of the pressure element used in the transducer, which would be atmospheric pressure. As a review of this application, refer to Figure 5, which shows that a change in

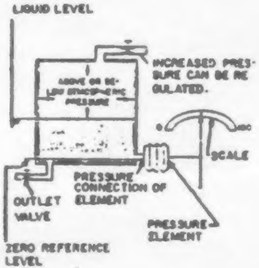

LIQUID LEVEL
ABOVE OR BELOW ATMOSPHERIC PRESSURE
INCREASED PRESSURE CAN BE REGULATED.
0
100
SCALE
PRESSURE CONNECTION OF ELEMENT
OUTLET VALVE
PRESSURE ELEMENT
ZERO REFERENCE LEVEL

Fig. 5

pressure above the liquid level would cause serious error in measuring the liquid level.

When tank pressure is other than that on the outside of the bellows, the transducer responds and indicates a false change in level.

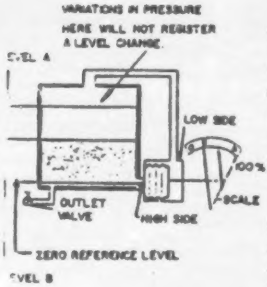

VARIATIONS IN PRESSURE
HERE WILL NOT REGISTER
A LEVEL CHANGE.
EVEL A
LOW SIDE
100%
SCALE
OUTLET
VALVE
HIGH SIDE
ZERO REFERENCE LEVEL
EVEL B

Fig. 6

By using a differential-pressure transducer to measure level, the error caused by variations in static pressure inside the tank is eliminated. Pressure at the top of the tank is applied to one side of a differential-pressure instrument as in Figure 6, while the other side of the instrument is connected to the tank. The point at which the instrument is attached to the tank is the reference or zero level position. By observing the application shown in Figure 6, it can be seen that a fluctuation in pressure in the tank will change the force on the outside of the differential-pressure transducer. Note, however, that, while this is happening, pressure on the liquid causes a force of the same amount to be exerted on the inside of the bellows. Thus, the uncontrolled fluctuations in pressure in the tank cause equal forces to be applied to both the inside and outside of the bellows, resulting in no movement of the instrument. The hydrostatic head of the liquid is the only variable that will cause a movement of the measuring device.

FLUID FLOW MEASUREMENT

By referring to Module 10F2, it can be seen that fluid flow is proportional to the square root of the difference in pressure across a differential producer such as an orifice plate. Difference in pressure is measured by a differential-pressure transducer.

Figure 7 shows an application for measurement of flow with a differential-pressure transducer.

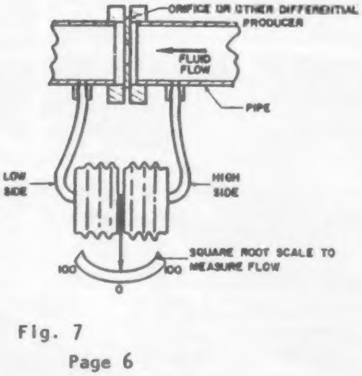

ORIFICE OR OTHER DIFFERENTIAL PRODUCER
FLUID FLOW
PIPE
LOW SIDE
HIGH SIDE
100
0
100
SQUARE ROOT SCALE TO MEASURE FLOW

Fig. 7

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LABORATORY

MATERIALS

Differential-pressure transducer with adjustable range.
Variable pressure regulator.
Air supply - 20 psig regulated.
Manometer with inches of water scale.

PROCEDURE

The purpose of this experiment is to enable the student to observe operation of a differential-pressure (d/P) transducer and to use standard test procedures to check calibration of the instrument.

1. Connect d/P instrument as shown in Figure 3.
2. Adjust air pressure regulator until manometer indicates zero. At this condition, atmospheric pressure is applied to both sides of d/P transducer.
3. Turn zero adjust screw on d/P transducer for an indication of zero differential pressure on scale.
4. Select a range in adjustable limits of instrument and adjust air regulator until manometer indicates selected full scale value.
5. If instrument reading is above or below full scale value, decrease or increase span as necessary to provide proper span on instrument. When performing step 5 for span adjustment, it will be necessary to make span adjustment and then reduce differential pressure to zero to observe result of span adjustment. This is true because a span adjustment provides multiplication of instrument's response.

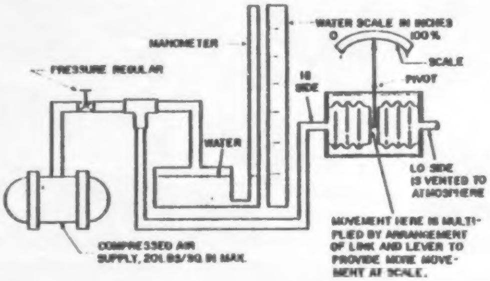
WATER SCALE IN INCHES
0
100%
MANOMETER
SCALE
PRESSURE REGULAR
PIVOT
HI SIDE
WATER
LO SIDE IS VENTED TO ATMOSPHERE
MOVEMENT HERE IS MULTIPLIED BY ARRANGEMENT OF LINK AND LEVER TO PROVIDE MORE MOVEMENT AT SCALE.
COMPRESSED AIR SUPPLY, 20LBS/SQ IN MAX.

Fig. 8

6. Return indicator on d/P transducer to zero by adjusting regulator until manometer indicates zero differential pressure.
7. Repeat step 3.
8. Repeat steps 3 through 7 until no further adjustment is necessary.
9. When zero and span adjustments have been made for proper indication of instrument at zero and one hundred percent of

d/P range, vary d/P in increments of 10% and list data in data table. To calculate % error, divide difference in indication between instrument and manometer by manometer indication and multiply by 100, or

$$(5) = \frac{[(2) - (3)]}{(3)} \times 100.$$

10. Draw a calibration curve by plotting manometer indication against instrument indications in Figure 9.

Note: Consult manufacturer's manual on specific instrument used for proper methods of zero and span adjustments as well as for calibration procedure.

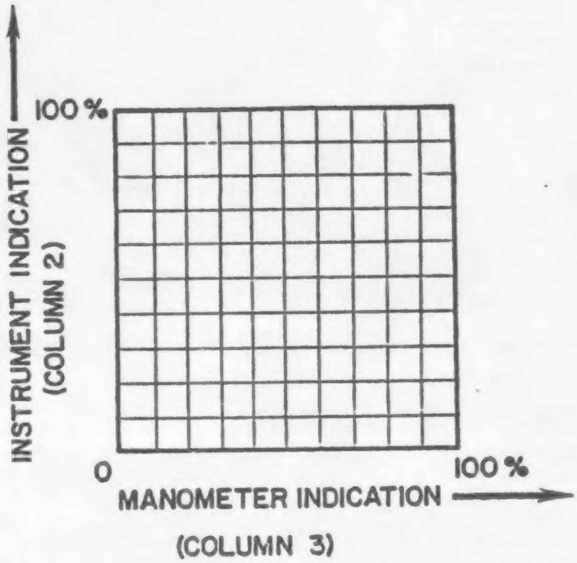

Fig. 9

DATA TABLE				
(1) Percent of Full Scale d/P	(2) Instrument Indication	(3) Manometer Indication	(4) Difference Between d/P Instrument and Manometer	(5) % Error
0				
10				
20				
30				
40				
50				
60				
70				
80				
90				
100				

SELF CHECK

1. Convert the following gage pressures to absolute pressures:

   3.0 psig to __________ psia.

   16.0 psig to __________ psia.

   152.0 psig to __________ psia.

   256.0 psig to __________ psia.

2. Describe two types of differential-pressure transducers.
3. Describe, in simple steps, calibration of a differential-pressure transducer.

4. Describe measurement of liquid level and fluid flow using a differential-pressure transducer.

REFERENCES

Petroleum Extension Service, University of Texas. Basic Instrumentation. Austin, TX: University of Texas Press, 1972.

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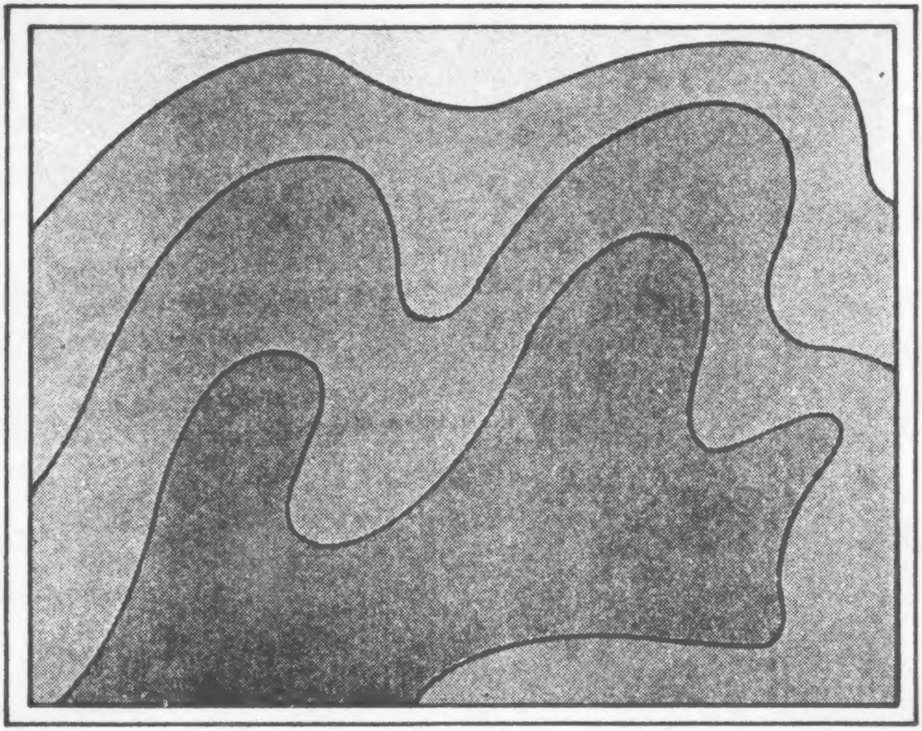
UNIFIED TECHNICAL CONCEPTS

MODULE 10 F 4

FLUID FLOW
MEASURING DEVICES



FLUID APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Most systems applications depend upon the precise manipulation of fluid flow quantities to achieve a high quality of control. Before flow can be controlled accurately by automatic means, it must first be measured. For this reason, one must understand how to measure fluid flow. This module will cover flow measurement techniques with emphasis on those most commonly used.

PREREQUISITES

Student should have completed Module 10-0, "Trandsucers" and Application Module 7F2, "Venturi Meter."

OBJECTIVES

To complete this module, the student should be able to:

- Given the appropriate equipment, make measurements of the variables that relate to fluid flow velocity, calculate flow quantities, and discuss the relationships of the variables to the rate of flow.
- Assemble and operate flow measuring systems in the laboratory.

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DISCUSSION

The ratelike quantity in the fluid systems is the amount of fluid flowing through a pipe, expressed as a volumetric or weight quantity per unit time. Such units are:

Gallons per minute
Barrels per day
Cubic feet per second
Pounds per hour

or any other desired units.

If the velocity of material moving through a pipe and the cross-sectional area of a given portion of that pipe are known, then the volume rate of flow can be determined from their product. If velocity is in ft/s and area in ft^2, then the volume rate is in units of $(ft/s)(ft^2) = ft^3/s$.

The standard approach to flow measurement is to use a portion of a pipe with known area and measure the time required for the fluid to travel through the specified length of pipe. The practice of flow measurement is, thus, a matter of measuring fluid velocity.

The usual approach to measuring fluid velocity incorporates a device which converts the kinetic energy of the moving material to a measurable signal. This is done with the help of transducers, devices which convert one form of energy to another.

Not only is it necessary to convert the kinetic energy to a measurable signal, but the signal must have an exact relationship to the flow rate. This relationship can be established by both analytical and empirical means.

HEAD TYPE FLOW MEASUREMENT

To understand flow measurement by head type flowmeters, consider a fluid flowing at a steady rate through a pipe with a constriction placed in it. If the fluid is incompressible, the same volume of fluid must pass through every section of the pipe in the same time interval (Figure 1).

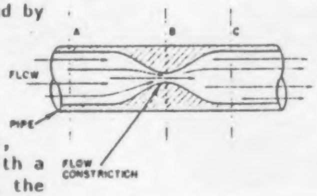

Fig. 1

Conforming to the laws of conservation of mass and energy, the mass entering any portion of pipe must equal mass leaving that portion during same time interval, and same is true for kinetic energy, as long as no energy is dissipated through friction. The fluid flow velocity is, therefore, increased in smaller section of pipe, resulting in an increase in kinetic energy per unit mass. In Concept Module 8-0, the principle of conservation of energy is applied to fluid flow, resulting in Bernoulli's equation. This fundamental equation relates in a general way the fluid velocity and pressure at different points in a pipe.

When a constriction is introduced in a pipe, a pressure difference appears across the constriction (called a "differential producer"). The pressure drop across the differential producer is usually measured in inches of water. The points in the pipe where the measurements are made are called taps and the location of the taps with respect to the differential producer is significant.

A basic application of flow measurement by differential pressure is shown in Figure 2, where a flat concentric orifice is flanged into the pipe to produce the differential pressure. The tap locations are fixed in the orifice flange at points one inch upstream and one inch downsteam from the orifice. The differential pressure is measured with a mercury manometer attached to the orifice flange (Figure 2). The pressure difference is proportional to the height difference in the two arms. At zero flow the mercury is at the same level on both sides of the manometer. The difference in levels h is greatest for the maximum flow.

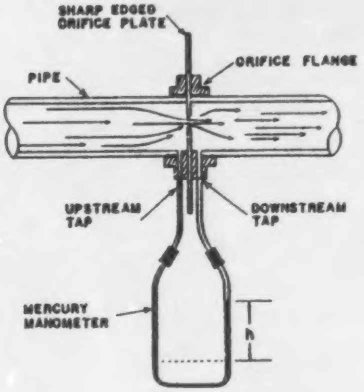

Fig. 2

The relationship of flow rate to differential height h, can be established empirically or described by theoretical formulas. The fact that such formulas exist is a major advantage of this simple type of flow measurement. Other more complicated flow measurement techniques must rely on empirical calibrations of the primary flow device.

A working equation has been derived to calculate the rate of flow through a differential pressure producer of known area and a pipe of known size at a given differential pressure. The working equation is:

$$Q = C_n\sqrt{\Delta p} \qquad (1)$$

where

C_n = constant for particular flow situation.
Δp = differential pressure developed across producer.
Q = calculated flow rate.

For given flow conditions values of C_n can be found in flow engineering books.

A magnetic flowmeter is another widely used method of flow measurement (Figure 3). The operation of a magnetic flowmeter is based on Faraday's law of induction, which states that the voltage induced in a conductor moving at right angles through a magnetic field is proportional to the velocity of the conductor moving through the field.

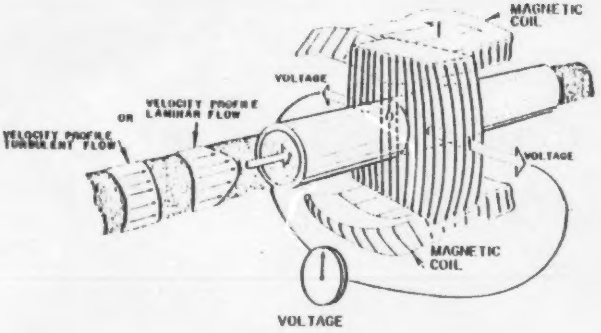
MAGNETIC COIL
VOLTAGE
VELOCITY PROFILE LAMINAR FLOW
OR
VELOCITY PROFILE TURBULENT FLOW
VOLTAGE
MAGNETIC COIL
VOLTAGE

Fig. 3

The moving conductor is the liquid and a magnetic filed is established at right angles to the pipe by magnetic coils. The voltage induced in the moving fluid is proportional to the fluid velocity and is detected by electrodes in contact with the fluid. This voltage is transmitted to a receiving instrument called a signal converter and is transformed to a scaled signal that represents a definite flow rate. For a particular meter, the strength of magnetic field is fixed as is the distance between the electrodes. The induced voltage is then purely a function of fluid velocity. Calibration of the magnetic flowmeter is established empirically by the manufacturer. The signal converter can be checked for accuracy by using a calibrator to simulate an electrical signal corresponding to a flow quantity.

FLOW MEASUREMENT WITH A PLATE TYPE ORIFICE METER

MATERIALS

One orifice flange mounted in 2" pipe with 0.5" or 0.75" diameter orifice. This item can be manufactured in any machine shop capable of producing material to within 5/1000 tolerance or purchased from one of several reputable flow measuring companies.

Pump that can deliver a flow of about 10 gal/min.

Mercury "U" tube manometer of a differential pressure measuring device.

PROCEDURE

The purpose of this procedure is to establish a calibration curve for a plate type orifice meter.

1. Connect the orifice and manometer as shown in Figure 2 and establish a convenient flow rate to yield a measurable height differential, h.
2. Measure the flow by weight or volume per unit time in a convenient tank.
3. Record the value as a maximum flow rate in Data Table 1.
4. Reduce the flow to give a 10% reduction of height differential, h. Measure and record in Data Table 1 the flow rate at the lower height differential, h.
5. Repeat step 4 for eight different measurements each successively reduced in height differential by approximately 10%.
6. Plot each flow rate versus the square root of the corresponding height differential h in accordance with Equation 1. That is, plot Q versus $\sqrt{h}$ (Figure 4). Note: Since the pressure differential Δp is proportional to the height differential h, Equation 1 can equally well be stated as $Q = C'_n \sqrt{h}$, where C'_n is merely a constant different from C_n. The plot of Q versus $\sqrt{h}$

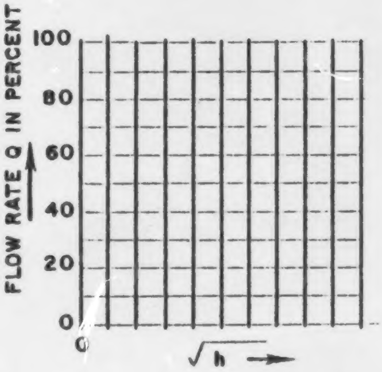

Fig. 4

should be linear and should be plotted on a graph (Figure 4).

7. From the plot in Figure 4, other flow rates for appropriate differential heights h can be determined directly.

DATA TABLE 1	
Flow Rate in Gal/Min	Differential (h) in Inches of water
1. (max)	(max)
2.	
3.	
4.	
5.	
6.	
7.	
8.	
9.	
10.	

FLOW MEASUREMENT WITH A TURBINE METER

MATERIALS

Flow nozzle of jet.
Impeller or fan blade mechanically connected to a small generator.
Voltmeter to measure output of generator.
Pump to produce a flow of about 10 gal/min.

PROCEDURE

The purpose of this procedure is to demonstrate the principle of flow measurement with a turbine meter.

When an impeller is placed in a pipe and is free to rotate, kinetic energy of the flowing fluid is converted to mechanical energy, causing the impeller to rotate. The speed of rotation is directly proportional to the fluid velocity. The rotary motion generates an electrical signal much like the moving fluid does in a magnetic flowmeter. This provides a very accurate means of flow measurement. It can be used for nonconducting fluids that cannot be measured by magnetic flowmeters. Calibration is done empirically by the manufacturer.

1. Arrange the water jet or flow nozzle in the end of a hose connected to the pump discharge.
2. Position the nozzle so a water stream emerging from it will start the impeller causing it to run the generator.
3. Measure the water flow and record a corresponding voltage output from the generator in Data Table 2.
4. Plot the generator output versus flow rate on a plot similar to Figure 4.

   This should produce a linear response of flow with respect to signal unless frictional losses in the impeller are significant. Thus, the relationship of signal to flow has been established.

DATA TABLE 2

Flow (Gal/Min)	Voltage
1.	
2.	
3.	
4.	
5.	
6.	
7.	
8.	
9.	
10.	

SELF CHECK

1. Given the appropriate equipment, make measurements of the variables that relate to fluid flow velocity, calculate flow quantities, and discuss the relationships of the variables to the rate of flow.
2. Assemble and operate flow measuring systems in the laboratory.

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Petroleum Extension Service, University of Texas. Basic Instrumentation. Austin, TX: University of Texas Press, 1964.

Spink, L.K. Principles and Practice of Flowmeter Engineering. 9th ed. Foxboro, MA: Foxboro Company, 1972.

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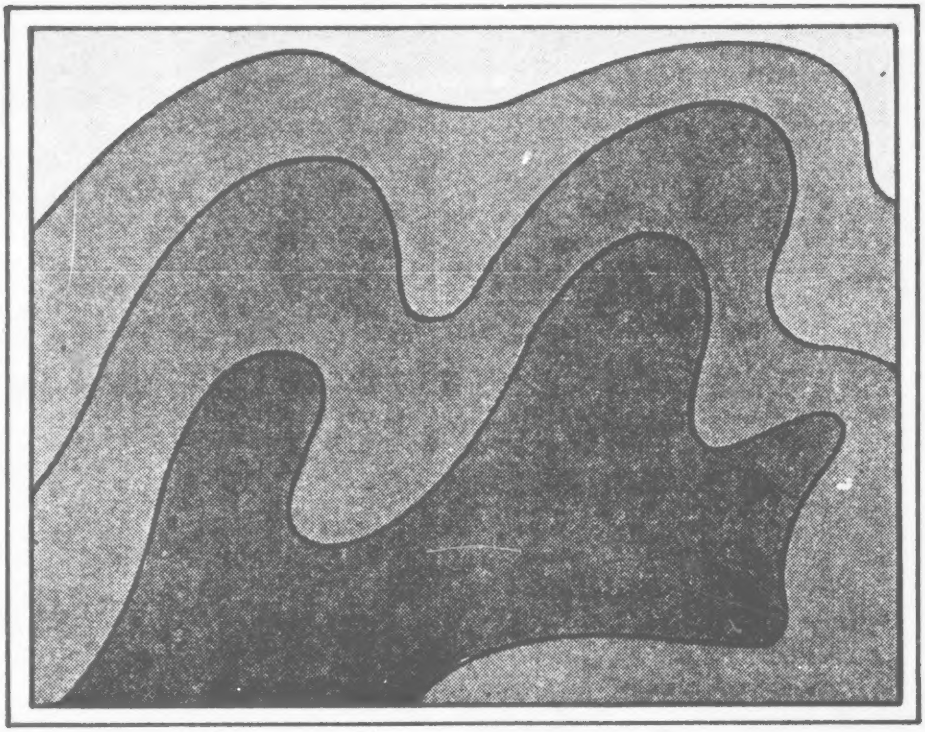
UNIFIED TECHNICAL CONCEPTS

MODULE 10 F 5

VACUUM GAGES



FLUID APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Vacuum technology, used in science and industry, deals with gases at pressures below one atmosphere. Modern techniques can produce ultrahigh vacuum, with pressures less than 10^{-9} millimeters of mercury (compared to the pressure of 760 millimeters of mercury at one atmosphere). Even in such a vacuum, there are many millions of gas molecules per cubic centimeter.

This module examines a variety of different gages used to measure vacuum. Some gages, such as mercury manometers, respond to the pressure exerted by the gas. Other gages, such as the thermocouple gage, depend upon the change of a physical property of the gas as pressure decreases. In the laboratory, the student will use different types of vacuum gages to measure gas pressure in a vacuum system as the gas pressure is reduced below atmospheric pressure.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers." We recommend that the student be acquainted with vacuum pumps as treated in Application Module 9F5, "Vacuum Pumps."

OBJECTIVES

Upon completion of this module, the student should be able to:

- State the pressure ranges implied by the following terms:

  Rough vacuum.
  Medium vacuum.
  High vacuum.
  Very high vacuum.
  Ultrahigh vacuum.

- Given the necessary information, calculate the mean free path of a gas molecule.

- Describe qualitatively how the following phenomena vary as gas pressure varies: Thermal conductivity and impact ionization
- Describe the operation of the following types of vacuum gages:

    Mechanical gage.
    Mercury manometer.
    McLeod gage.
    Thermocouple gage.
    Pirani (resistance) gage.
    Ionization gage.

- State the approximate range of pressure for which each of the above types of gages is useful.
- Given the appropriate equipment, measure the pressure in a vacuum system when the pressure is reduced below atmospheric pressure.

DISCUSSION

This module and Application Module 9F5 are two related modules concerned with vacuum technology. In this module, methods for measuring vacuum are emphasized; and in Module 9F5, methods for producing it are emphasized.

The word "vacuum" means "empty space." But no vacuum is completely empty: There are always many gas molecules present within a so-called vacuum. As used here, the word "vacuum" refers to a space filled with a gas at a pressure less than one atmosphere.

According to this definition, a vacuum can be produced rather easily; for example, by a human being sucking on a straw, or by an octopus using the suction cups on its arms. Vacuum systems used in science and industry employ chambers (usually of metal) evacuated by pumps. Pressures that very far below atmospheric pressure can be attained in such systems. This is the regime of vacuum technology addressed in this module.

A discussion of the units employed in the measurement of vacuum now is in order. The pressure exerted by a gas at one atmosphere pressure will support a column of mercury 760 millimeters high. As the pressure decreases, the height of the column that can be supported by the gas pressure decreases. Thus, gas pressures usually are expressed in the unit "millimeters of mercury," which refers to the height of the column of mercury that could be supported by the gas. Mercury manometers indicate pressure directly from the height of mercury in a tube. As pressures become very low (much less than 1 millimeter of mercury), direct observation of the height of a mercury column becomes impossible. Yet the unit "millimeter of mercury" still is used at very low pressures, even down to 10^{-10} mm of mercury and below.

Because the unit "millimeter of mercury" is cumbersome to use, it has been replaced in common use by the unit "torr," in honor of Torricelli, who invented the mercury barometer. Although there are some differences in the exact definition, for practical purposes one torr is equal to one millimeter of mercury. The torr unit will be used throughout the remainder of this module.

Vacuum technology covers a wide range of pressures, denoted by various terms. Table 1 summarizes some of the terminology commonly used. Slighly different definitions of the terms are used in different sources, but the tabulation here shows the general classification for different levels of vacuum. Of course, different measurement techniques are used in the various regimes. The lower limit to the range of ultrahigh vacuum continually decreases as vacuum technology progresses.

TABLE 1. VARIOUS LEVELS OF VACUUM

Level of Vacuum	Pressure Range (torr)
Rough vacuum	760 - 1
Medium vacuum	$1 - 10^{-3}$
High vacuum	$10^{-3} - 10^{-6}$
Very high vacuum	$10^{-6} - 10^{-9}$
Ultrahigh vacuum	below 10^{-9}

The pressure also is related to the density of molecules in the gas by Equation 1.

$$p = nkT \tag{1}$$

where
- p = pressure in units of force per unit area (in dyne/cm^2).
- n = number of gas molecules per cm^3.
- k = Boltzmann's constant, numerically equal to 1.38×10^{-16} erg/K.
- T = absolute temperature K.

The relationship between pressure in dynes and torrs is expressed in Equation 2.

$$1 \text{ dyne/cm}^2 = 7.50 \times 10^{-4} \text{ torr}$$

or

$$1 \text{ torr} = 1333 \text{ dyne/cm}^2 \tag{2}$$

Equations 1 and 2 are employed in Example A to solve a practical problem.

EXAMPLE A: DENSITY OF GAS MOLECULES

Given: In a system, there is a gas pressure of 10^{-9} torr and a temperature of 300 K.

Find: The number of gas molecules per unit volume.

Solution: According to Equation 2, 10^{-9} torr is equal to 1.333×10^{-6} dyne/cm^2, which yields the following when substituted into Equation 1:

$$
\begin{aligned}
p &= nkT \\
1.333 \times 10^{-6} &= nkT \\
1.333 \times 10^{-6} &= (n)(1.38 \times 10^{-16})(300) \\
n &= (1.33 \times 10^{-6}\ (1.38 \times 10^{-16})(300) \\
n &= 3.22 \times 10^{7}/\text{cm}^{3}
\end{aligned}
$$

Thus, even in an ultrahigh vacuum, there can be more than 30 million gas molecules in a cubic centimeter of space.

The composition of gas changes as pressure decreases. At pressures from 760 torr down through the medium vacuum range, gas is mainly residual air and has a chemical composition similar to that of air, about 80% nitrogen and 20% oxygen. As pressure drops to the high-vacuum range, the residual air is gone; and the gas in the system is that released by the surfaces in the system. In the high-vacuum range, the gas may be mostly water vapor, which arises from the release of water vapor absorbed on the surfaces. In the ultrahigh vacuum regime, the residual gas may be mostly hydrogen, coming from permeation of hydrogen entrapped within the materials from which the vacuum system is constructed. This change in composition is important for pressure measurement because different methods of measurement have varying sensitivities for different gases.

An important concept in vacuum technology is the "mean free path" of a gas molecule. The molecules in a gas are in random motion, colliding with each other and changing their direction of motion after each collision. The "mean free path" of a gas molecule is defined as "the average distance that a gas molecule travels between two successive collisions." Of course, as gas pressure decreases, the molecules are farther apart, and the mean free path increases. The mean free path is given by Equation 3.

$$\lambda = \frac{C_g}{n} \qquad (3)$$

where

λ = mean free path.
C_g = constant, characteristic of the particular gas.
n = density of gas molecules.

According to Equation 1, the mean free path is inversely proportional to the pressure.

For air, C_g has the value of 1.66×10^{14} cm^{-2}. The value of C_g will be somewhat different for other gases, being higher for light monatomic gases, such as He, and slightly lower for polyatomic gases, such as CO_2. However, C_g does not vary greatly between different gases. Table 2 gives quantitative values of λ for air. At pressures near one atmosphere, the mean free path is very short. As pressure drops, the mean free path becomes larger and can be very large under conditions of very high vacuum or ultrahigh vacuum.

TABLE 2. MEAN FREE PATH (AIR AT 25°C)

Pressure (torr)	Mean Free Path λ (cm)
760	6.7×10^{-6}
1	5.1×10^{-3}
10^{-3}	5.1
10^{-6}	5.1×10^{3}
10^{-9}	5.1×10^{6}

As the mean free path becomes large as pressure decreases, it eventually becomes larger than the dimensions of the vacuum chamber. Then a gas molecule will make most of its collisions with the walls of the chamber and infrequently will collide with another gas molecule. It will travel through the vacuum chamber from wall-to-wall without encountering another gas molecule.

In order for vacuum technology to be used in practical applications, the level of the vacuum must be measured. There are many different methods used to measure gas pressure in a vacuum system. Because the pressures of interest in vacuum systems cover such a broad range, no single method is applicable for all pressure ranges. Different types of gases are useful in different ranges of pressure, and different gages may have special advantages or disadvantages for specific applications. Many different types of gases, therefore, are used in vacuum technology. The discussion below will describe the operation of some of the most frequently-used gages.

Some gages respond to the total pressure exerted by the gas. Such gages include the mechanical gage, the mercury manometer, and the McLeod gage. These gages generally are useful only in higher ranges of pressure and do not always offer continuous recording of pressure.

Other gages operate by sensing some gas property, such as thermal conductivity, that changes with pressure. Such gages record continuously and are useful in lower ranges of pressure. The gages of this type that will be discussed include the thermocouple gage, the Pirani (or resistance) gage, and the ionization gage.

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THE MECHANICAL GAGE

In a mechanical diaphragm gage, a flexible metal diaphragm separates two chambers. One chamber is connected to the vacuum system whose pressure is to be measured; the other is evacuated to low pressure. As the pressure in the vacuum chamber changes, the diaphragm flexes slightly because of the varying air pressure on one side. The diaphragm is linked mechanically to a meter, so that the flexure of the diaphragm is displayed directly on the meter as a pressure. Often such gages are constructed as circular meters covering a specific range of pressure, such as 0-760 torr, or 0-20 torr.

Of course, at low pressures such gages lose sensitivity. The practical range covered by a gage in which the diaphragm simply is linked mechanically to the pointer in the meter is perhaps 0.1 torr to 760 torr. More elaborate means of coupling the motion of the diaphragm to the meter are possible; for example, optical or electrical coupling. With these methods, the range of operation of such a gage can be extended to lower pressures.

MERCURY MANOMETER

A manometer consists of a U-shaped glass tube filled with a liquid, usually mercury. One end is connected to the vacuum system, as indicated by Figure 1. The other end may be open to the air. As the pressure in the vacuum system is reduced, the level of mercury rises in the tube attached to the vacuum system. The difference in the height Δh between the levels in the two arms is proportional to the difference in pressure between the two arms. Thus, measurement of the height Δh (read from the graduated scale mounted next to the U-tube) gives a measure of the pressure in the vacuum system. The pressure p is given by Equation 4.

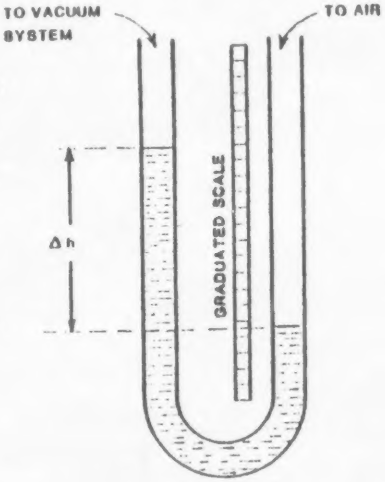

FIG. 1

$$p = p_a - \Delta h \qquad (4)$$

where

p = pressure in vacuum system in torr (mm of Hg).
p_a = ambient air pressure in torr (mm of Hg).
Δh = differential height.

The differential pressure between air and vacuum is sufficient to support a column of mercury 760 mm high, which, as described before, leads to the definition of the unit of pressure as a "millimeter of mercury," with ambient air having a pressure of 760 mm of Hg.

The range over which the mercury manometer is useful is determined by its ability to measure the height Δh, although by eye, one can measure it to a precision of about 0.1 mm. Thus, if the pressure were 1 torr, the error in the pressure would be about 10% because of the uncertainty in measurement of Δh. At lower pressures, the percentage error would be larger. The mercury manometer, therefore, is useful for pressure measurements over the range of from 1 torr up to 760 torr. Its range could be extended to lower values by use of a microscope with which to meausre the level.

Over the pressure range for which it is applicable, the mercury manometer provides a simple, easy-to-use gage, reading directly without any need of calibration.

THE MCLEOD GAGE

The McLeod gage also involves measurement of the height of a column of mercury in a glass tube. It employs compression of the gas by a known amount and extends the range of measurement below the range covered by the mercury manometer.

The basic structure of the McLeod gage is illustrated in Figure 2. It consists of a glass bulb with a capillary tube on the top. The bulb is connected to the vacuum system through a side arm that has a capillary section in parallel with the main tube. This capillary has the same diameter as the capillary on top of the bulb. There also is a means for raising and lowering the level of mercury in the system, shown here as an "auxiliary pump" connection.

When the mercury is lowered far enough that the bulb is connected to the vacuum system through the side arm, the pressure p in the bulb will be the same as the pressure in the vacuum system. Then the mercury level is raised so that the bulb is cut off from the side arm, and the gas is compressed into the capillary at the top of the bulb.

Since the two capillaries have the same bore size, surface-tension effects are canceled out. The difference in level of mercury in the two capillaries

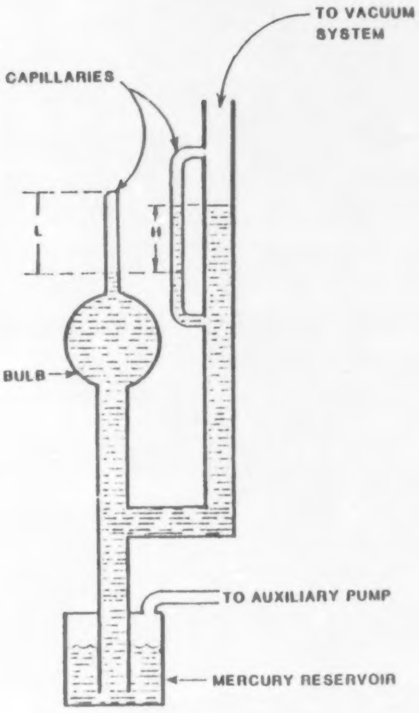

FIG. 2

arises from the pressure difference due to compression. The pressure p in the vacuum system is related to the geometrical factors of the gage by Equation 5.

$$p = \frac{Ah_1h_2}{(V - Ah_2)} \qquad (5)$$

where

p = pressure of vacuum system.
A = cross-sectional area of either capillary.
h_1 = height of mercury in capillary attached to side arm.
h_2 = height of mercury in capillary attached to bulb.
V = volume of bulb.

For a known gage construction, the values of A and V will be known, and the pressure measurement may be accomplished by measuring h_1 and h_2. If one allows the capillary to fill a constant, predetermined level, h_2 will be a known constant value; and one will have to read only h_1 from the graduated scale.

The use of compression allows a small pressure to be translated into a larger difference in height, as compared to the mercury manometer; therefore, the Mcleod gage is useful at lower values of pressure, down to values as low as 10^{-6} torr. Because the gas in the bulb must be compressed, the gage cannot be used at pressures near atmospheric pressure. The upper limit of the useful range of pressure for the McLeod gage is approximately 100 torr.

The McLeod gage, therefore, covers a wide range of pressures and is a direct-reading instrument that responds directly to pressure. Thus, it often is used as a calibration device to calibrate other gages such as the thermocouple and the Pirani and ionization gages to be described later.

The McLeod gage has the disadvantage that it does not respond to condensable vapors such as water vapor. It also is somewhat cumbersome to use and does not provide continuous readings. Therefore, after calibration, other gages, such as the thermocouple gage, generally are employed for routine pressure monitoring.

THE THERMOCOUPLE GAGE

The operation of the thermocouple gage depends upon the cooling of a heated wire by thermal conduction through a gas. Thermal conductivity is measured by the extent to which a substance carries heat into its interior. The thermal conductivity k of a gas at temperature T is given by Equation 6.

$$k_t = \left(\frac{8\ m\ k\ T}{9\pi}\right) c\ n\ \lambda \qquad (6)$$

where

k_t = thermal conductivity of a gas at temperature T.
m = mass of gas molecules.
k = Botzmann's constant (as previously defined).
T = temperature of gas.
c = specific heat of the gas.

According to Equation 3, the mean free path is inversely proportional to n, so that the thermal conductivity will be independent of gas pressure. This relationship will be true for the range of gas pressures for which the mean free path is reasonably small. But as the pressure becomes low enough, the mean free path becomes comparable to the dimensions of the vacuum chamber. Then the mean free path cannot continue to increase with decreasing pressure, but remains constant, approximately equal to the size of the chamber. Then, as pressure decreases still further, thermal conductivity decreases, which, in turn, means that the heated wire cannot have heat removed from it by the gas as effectively as at higher pressures, and that the temperature of the wire increases. The temperature of the wire is measured by a thermocouple in contact with it.

From the description of thermal conductivity above, the thermocouple gage is useful over a limited range of pressures. At high pressures, thermal conductivity of the gas is independent of pressure, and the gage does not respond to changing pressure.

Thermocouple gages are available commercially as packaged devices designed to be inserted into the vacuum system, with electrical leads emerging from a feed-through. Two leads are used to monitor the voltage from the thermocouple and are used as the input to a calibrated meter, from which the pressure can be read directly. Two other leads are utilized to supply a calibrated electrical current that heats the wire. The current must be held at a constant value. The meter for a thermocouple gage usually is accompanied by a separate meter to monitor the current and to ensure that it remains constant.

The range of pressure covered by the thermocouple gage is limited by the physical phenomena described above. The thermocouple gage is useful over approximately the range from 10^{-4} torr to 10 torr. At higher pressures, thermal conductivity of the gas is independent of pressure, as earlier described. At lower pressures, thermal conductivity becomes so low that the gage is not sensitive to further changes in thermal conductivity.

THE PIRANI GAGE (OR RESISTANCE GAGE).

The Priani gage, or resistance gage, also depends upon the change of thermal conductivity of the gas with pressure. The gage has an electrically-heated wire cooled by the gas, and temperature of the wire depends upon gas pressure. The electrical resistance of the wire depends upon its temperature. Thus, measurement of the resistance of the wire will give a measurement of the gas pressure.

Often the measurement is performed with a Wheatstone bridge circuit as illustrated in Figure 3. The resistances R_2 and R_4 are fixed. The value of the variable resistor R_3 is changed until no current flows through the galvanometer G. Then the resistance R_1 of the gage is determined from Equation 7.

$$R_1 = \frac{R_2 R_3}{R_4} \qquad (7)$$

In order to calibrate the response of the gage, one must calibrate the response of the resistance R_1 against some other gage; for example, a McLeod gage.

The Pirani gage is useful over the pressure range of about 10^{-4} torr to 10 torr, for the same reasons as were discussed for the thermocouple gage.

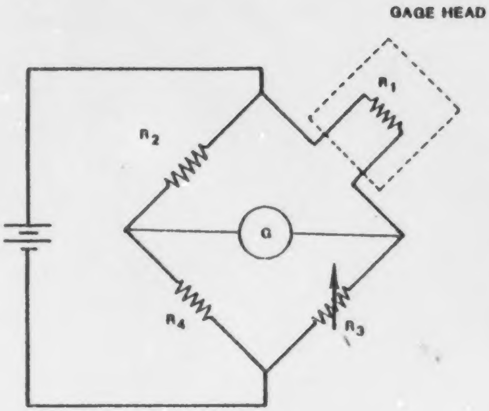

FIG. 3

THE IONIZATION GAGE

There is a variety of different types of ionization gages in use. We shall describe only the so-called "hot cathode ionization gage." The structure of this gage is illustrated in Figure 4. The fine-wire filament is heated electrically. Electrons are driven off the surface of heated metals in a phenomenon called "thermionic emission"; therefore, the heated filament serves as a source of free electrons.

The filament is surrounded by a wire grid held

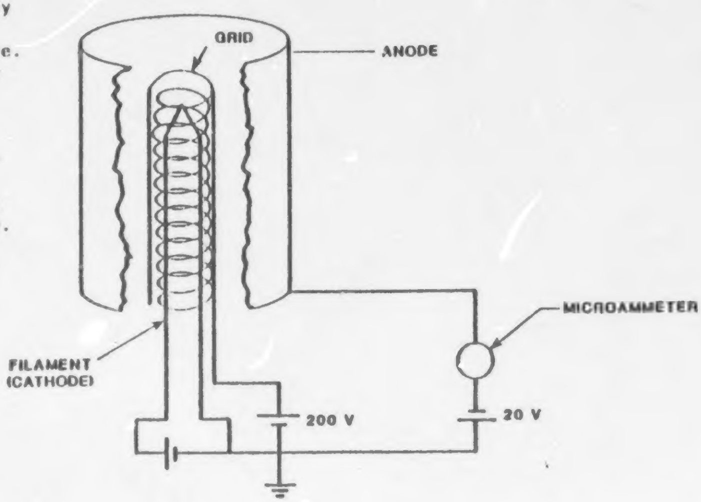

FIG. 4

at a potential of, perhaps, 200 V above that of the cathode. Thus, the electrons are accelerated toward the grid, depicted in Figure 4 as a wire helix surrounding the filament. The electrons acquire a large kinetic energy and may collide with gas molecules and ionize them, producing free positive ions. The free positive ions then travel to a collecting anode, shown in Figure 4 as a solid cylindrical shell surrounding the grid and filament. The anode is held at an electrical potential of about 20 V below that of the filament. Thus, electrons from the filament do not reach it, although the positive ions are drawn to it. This process results in an electrical ion current, which can be read on the microammeter.

The rate of ion production is proportional to the density of gas molecules. The more gas molecules present, the more likely that an electron will collide with one and produce a free ion. The positive ion current, therefore, is proportional to the gas pressure, as expressed by Equation 8.

$$I_p = G\, I_e\, p \tag{8}$$

where

I_p = ion current.
G = gage sensitivity.
I_e = electron current from filament.
p = gas pressure.

The factor G depends upon the nature of the gas in the chamber and upon the applied voltages; therefore, to calculate G is very difficult, and the value of G usually is determined by a calibration. Ionization gages must be calibrated against other gages, often McLeod gages, where their respective ranges overlap.

Hot cathode ionization gages are useful over the pressure range from about 10^{-8} torr to 10^{-3} torr. At higher pressures. the heated filament would burn out in the residual air; therefore, one must ensure that the ionization gage is not turned on until the pressure is reduced to a safe level.

The lower limit to the useful pressure range is determined by the production of X-rays by the electrons. The X-rays strike the anode and produce a spurious background current. There are additional variations of the ionization gage, which allow use of the ionization gage to measure pressures below 10^{-8} torr.

This module has described the operation of several different types of gages capable of measuring the pressure of gas in a vacuum system. Table 3 summarizes the ranges of pressures over which these gages are useful. Although the gages described here include some of the more important ones, there are other types, some of which are capable of measuring pressures down to 10^{-14} torr, or even below. The values given in Table 3 must be considered as approximate ranges. Variations of some of the devices have been developed to operate at pressures outside these limits. The purpose of Table 3 is to give a general indication of the pressure range in which a given gage is most useful.

TABLE 3. USEFUL RANGES FOR VARIOUS PRESSURE GAGES

Gage	Useful Range (torr)
Mechanical Diaphragm	0.1 - 760
Mercury Manometer	1 - 760
McLeod	10^{-6} - 100
Thermocouple	10^{-4} - 10
Pirani	10^{-4} - 10
Hot Cathode Ionization	10^{-8} - 10^{-3}

MEASUREMENTS WITH VACUUM GAGES

MATERIALS

Vacuum System, including:

1. Mechanical pump (e.g., Welch Scientific).
2. Vacuum gages; at least two required and at least 3 desirable; for example, the following is a suitable combination:
   a. Circular mechanical gage (e.g., Wallace and Tierman Co.).
   b. McLeod gage (e.g., Bendix Co.).
   c. Thermocouple gage (e.g., Veeco).
3. Valve between pump and vacuum system.
4. Flanges and couplings, as needed.

PROCEDURE

The student will learn to use pressure gages by employing at least two different types of gages to measure the pressure in a vacuum system as the pressure is reduced below atmospheric pressure. The vacuum system should be set up beforehand since to require the student also to set up the system is beyond the scope of this module. The vacuum system should incorporate at least two different gages; three different types would be preferable. These combined gages should cover a range of pressures from one atmosphere (760 torr) down to a suitably low value. These procedures will assume that a mechanical gage, a McLeod gage, and a thermocouple gage are available. The procedures can be modified to employ a different set of gages.

1. Close valve and turn on vacuum pump.

2. Open valve, and observe decreasing pressure indicated on mechanical gage. Record pressure in Data Table. When pressure has reached a value within range of McLeod gage, close valve to stop pumping.

3. Measure pressure with McLeod gage; record in Data Table. With reference to Figure 2, lower the level of mercury in

gage to below position of side arm. Then raise level so that gas in bulb is compressed into capillary on top of bulb. Mercury should be high enough so that it partially fills capillary. Measure the heights h_1 and h_2, as defined in Figure 2.

4. Calculate pressure, using Equation 5. Use values of V and A supplied by manufacturer of gage. Record pressure.

5. Compare pressure obtained in Step 4 to pressure indicated by mechanical gage.

6. Open valve and continue pumping. Pump until pressure reaches a value within range of thermocouple gage. Record pressure. This value may be checked by periodically stopping pumping and using McLeod gage to measure pressure, using Steps 3 and 4. When the pressure is low enough, proceed to next step.

7. Turn on thermocouple gage power supply. Use current-adjusting set screw to set calibrated current at value specified by manufacturer.

8. Read and record pressure on pressure scale. Notice that pressure is indicated on a logarithmic scale. Record pressure. Compare the value to that obtained using McLeod gage.

9. Open valve, and continue pumping. Observe decreasing readings on thermocouple gage scale. Check current periodically to ensure that it remains at proper value. When pressure has stopped decreasing, record the limiting value of pressure obtained.

10. How does this experiment demonstrate the principles examined in the Discussion?

DATA TABLE

Mechanical Gage Pressure	McLeod Gage			Thermocouple Gage	
	Measured Pressure		Calculated Pressure	Pressure	Limiting Pressure
	h_1	h_2			

SELF CHECK

1. State the pressure ranges implied by the following terms:

   Rough vacuum.
   Medium vacuum.
   High vacuum.
   Very high vacuum.
   Ultrahigh vacuum.

2. What is the mean free path of a molecule in air at a pressure of 10 torr and at a pressure of 10^{-11} torr?

3. Describe qualitatively how these phenomena vary as gas pressure varies:
   Thermal conductivity.
   Impact ionization.

4. Describe the operation of the following types of vacuum gage:

   Mechanical gage.
   Mercury manometer.
   McLeod gage.
   Thermocouple gage.
   Pirani (resistance) gage.
   Ionization gage.

5. State the appropriate range of pressure for which each of the above gages is useful.

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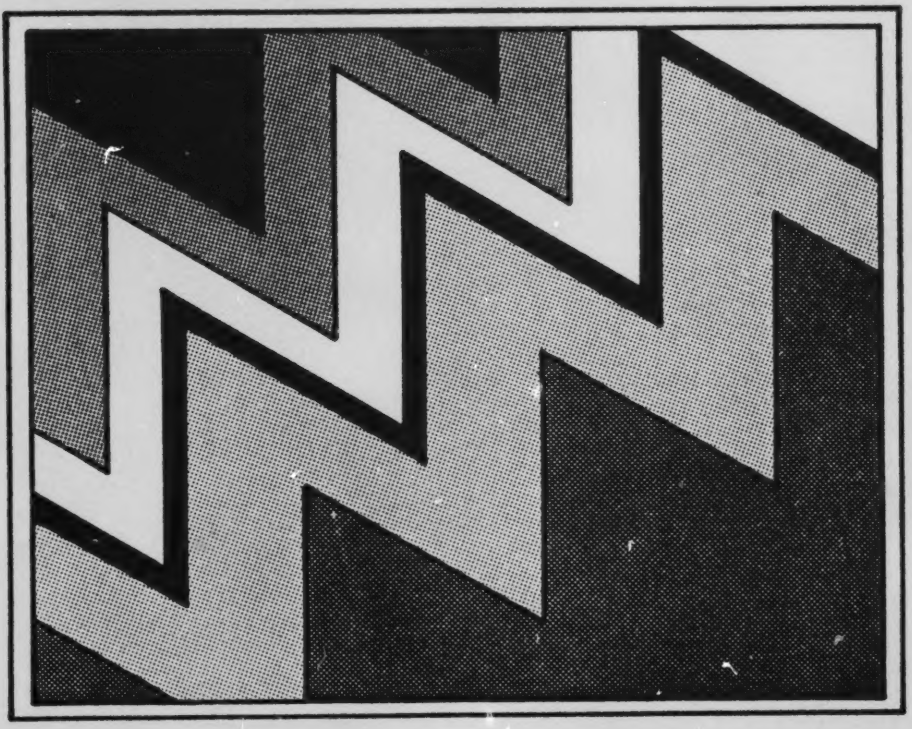
UTC
UNIFIED TECHNICAL CONCEPTS

MODULE 10 E 1
METER MOVEMENTS



ELECTRICAL APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest TERC - SW

102

INTRODUCTION

The heart of many electrical measuring instruments is the meter movement. Meter movements are transducers that use both electrical and mechanical energy. In a meter movement, an electrical current flows through a coil of wire to produce a magnetic field, which tends to align itself with the magnetic field of a permanent magnet. A pointer attached to the coil indicates the value of the current flowing through the coil.

This module will discuss the operation and applications of meter movements. In the laboratory, the student will construct a voltmeter and an ammeter.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers"; and Application Modules 1E3, "Electric Forces and Fields," and 1E4, "Magnetic Forces and Fields."

OBJECTIVES

Upon completion of this module, the student should be able to:

- List three major types of meter movements and an application of each type.
- Draw and label a sketch that illustrates the major components of a stationary-magnet/moving-coil meter movement; and explain its operation.
- Draw and label diagrams of the circuits used in the following types of meters:

  Voltmeter.
  Ammeter.
  Ohmmeter.

- Explain, with the use of a schematic diagram, how the internal resistance of a meter movement can be determined.

- Given the appropriate equipment, construct and operate a single-scale voltmeter and a single-scale ammeter.

DISCUSSION

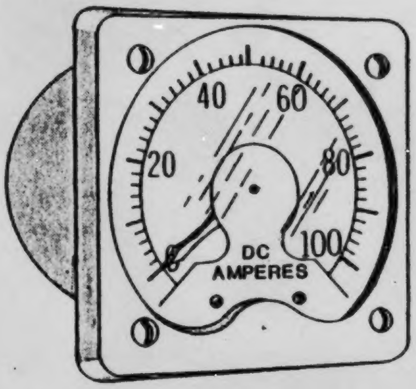
The ammeter and the voltmeter — two types of meter movement instruments used for switchboard and control applications — are depicted in Figure 1. They represent the many different electrical measuring instruments, the fundamental tools of the electrical industry.

These instruments are essential to the evaluation of various electrical quantities under a variety of conditions. Thus, an understanding of the operating principles and the construction of instruments is an indispensible aid in their proper application.

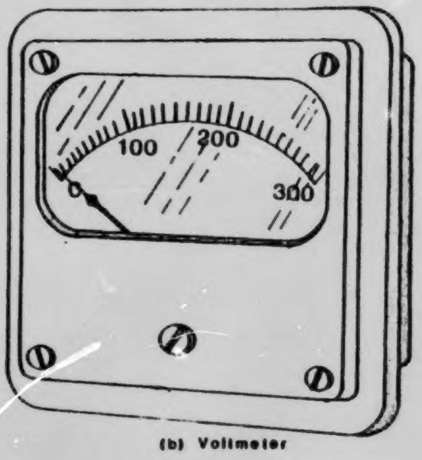
All common electrical meter movements operate as the result of magnetic fields produced by current flow through a coil of wire. The following three major types are necessary components of instruments used for measurements under the many conditions encountered in modern technology:

- Stationary magnet. Moving-coil mechanisms are the most common. They consist of a stationary magnet and a coil free to rotate through an angle. These meters provide high sensitivity and rapid response because of the small mass that must be moved.
- Stationary coil. Moving-magnet mechanisms are less sensitive and slower to respond, but are more rugged. They sometimes are used in the measurement of large currents.
- Stationary coil. Moving-coil mechanisms are used in the measurement of a.c. quantities. (The most common example of this type is the a.c. Wattmeter discussed in Module 6EI, "Electrical Power Measurement.")

All of these meter movements consist of a movable magnetic field suspended in a stationary magnetic field. The strength of one or both of the fields is proportional to current flow through the device. The remainder of this module is a description of the operation of the most common stationary-magnet/moving-coil mechanisms. The other types of meter movements operate according to the same principles.



(a) Ammeter



(b) Voltmeter

FIG. 1

STATIONARY-MAGNET/MOVING-COIL METERS

The stationary-magnet/moving-coil instrument illustrated in Figure 2 is used to measure undirectional currents, such as those supplied by a battery, rectifier, or d.c. generator. A strong permanent magnet is mounted rigidly in order that the magnetic field it provides will be of fixed position and polarity. The field is concentrated and made uniform across the air gap by soft iron pole pieces and a soft iron stationary core. Figure 3 is a more detailed diagram of the permanent magnet, pole pieces, and core.

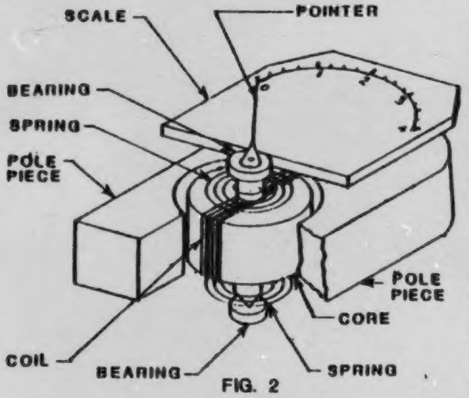


FIG. 2

A coil (Figure 4) pivoted to rotate on jeweled bearings is located in such a manner that it is free to move in the gap between the pole pieces and the core. The coil is connected to the electrical circuit through torque springs that provide the restoring force of the instrument and also carry current to the coil.

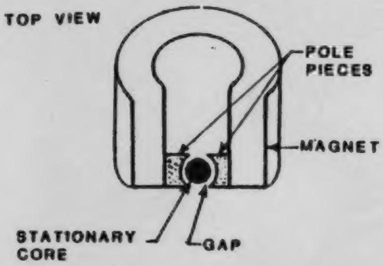


FIG. 3

The moving element must be light in weight to respond quickly to changing current and be strong enough to resist the forces of overloads.

With no current flowing through the coil, no magnetic force acts upon the coil. It is held in the "zero" position by the coil springs. When a current flows, magnetic forces are produced on the movable coil (Figure 5). These forces result in a rotational torque that opposes the torque applied by the spring. The coil rotates to a new position, at which the two torques are of equal magnitude. The energy of the magnetic field is converted to potential energy of the coiled spring. A pointer appropriately attached to the coil moves around a properly-calibrated scale to indicate the value of the current flowing through the coil.

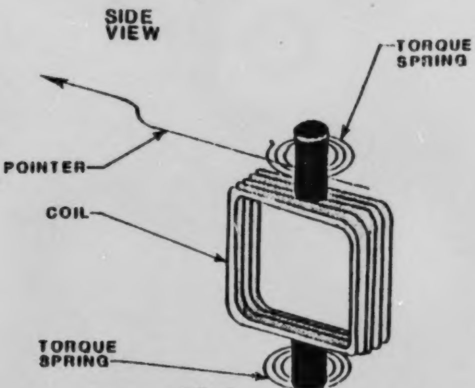


FIG. 4

All such mechanisms respond to the magnitude of current through the coil and to the magnitude of the stationary magnetic field. The meter scale, however, may be calibrated to indicate a measurement of any quantity proportional to coil current.

AMMETERS

When direct currents that exceed the current-carrying capacity of the spring must be measured, the permanent-magnet and moving-coil mechanism is used in conjunction with a shunt. Figure 6 is a schematic representation of such an arrangement, where M represents the meter movement and R_S represents the shunt resistance. The instrument coil and shunt are connected in parallel; they divide the current in inverse ratio to their resistances. Instruments and shunts are calibrated as a unit and can be utilized to measure relatively-high direct currents. Shunts capable of carrying as much as 100 amperes frequently are assembled inside instrument cases, and external shunts are available in a variety of ratings up to many thousands of amperes.

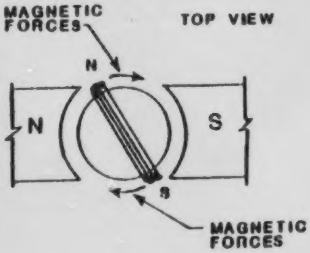


FIG. 5

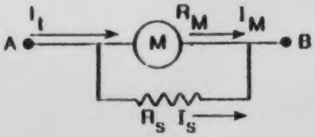


FIG. 6

VOLTMETERS

Stationary-magnet/moving-coil instruments also can be adapted to measure d.c. voltage. In this case, the instrument coil is connected in series with a resistor to limit the current to a value that safely can be carried by the coil and springs. Figure 7 shows the fundamentals of a d.c. voltmeter, where M is the meter movement and R_M is the series resistance.

Since the current is directly proportional to the applied voltage, the instrument can be calibrated in terms of d.c. volts. Series resistors, or "voltage multiplying resistors," as they sometimes are called, may be assembled within the instrument case or connected externally.

BASIC D.C. VOLTMETER CIRCUIT

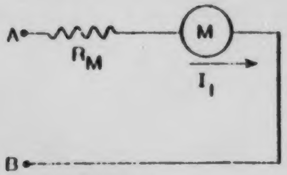


FIG. 7

OHMMETERS

A single-scale ohmmeter also can be constructed from a stationary-magnet/moving-coil meter movement (Figure 8). In this case, the instrument coil M is connected in series with a battery and a variable resistor R_y.

SINGLE SCALE OHMMETER CIRCUIT

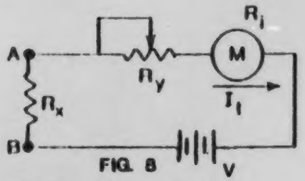


FIG. 8

The unknown resistor, R_x, placed across the ohmmeter at points A and B, becomes a part of the circuit and can be measured using simple d.c. theory. The scale of the ohmmeter, calibrated in ohms, indicates the resistance directly.

SUMMARY

Meter movements are energy convertors that change part of the energy of a magnetic field into mechanical potential energy stored in a coiled spring. A needle attached to the moving coil (or magnet) indicates the amount of energy stored in the spring and, thus, the magnitude of the current flowing through the coil of the meter. Appropriate circuitry can be used to calibrate the meter to measure voltages, currents, and unknown resistances.

DETERMINATION OF METER INTERNAL RESISTANCE

MATERIALS

Digital voltmeter (optional).
Volt-Ohm-Milliammeter (VOM).
2.5-k variable resistor.
Low-voltage power supply.
Meter movement. [For this and all subsequent labs, a meter movement with a full scale current of 1 ma is assumed (I_{FS} = 1 ma).]
Clip leads.

PROCEDURE

Before a voltmeter, an ohmmeter, or an ammeter can be constructed, the internal resistance of the basic meter movement must be known. If the internal resistance is not given on the instrument, it can be determined by the series-resistor-method (Figure 9).

1. Connect components as shown schematically in Figure 9.

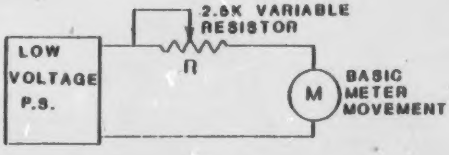


FIG. 9

2. Set R to provide maximum resistance. Set power supply for an output voltage of approximately one volt.
3. Adjust R until the meter indicates full scale. Increase power-supply voltage if necessary.
4. Disconnect the circuit and measure R with the VOM. Call this reading R_1; record in Data Table 1.
5. Reconnect the circuit and adjust R until the meter indicates 1/2 scale. (Do not change power-supply voltage.) Measure R as before and call this reading R_2. Record.
6. The internal resistance of the meter R_M is determined from the following equation (see sample calculation):

$$R_M = R_2 - 2\,R_1.$$

Record the value of R_M in Data Table 1.

EXAMPLE CALCULATION

$R_1 = 1256$ ohm

$R_2 = 2620$ ohm

$2\ R_1 = 2512$ ohm

$R_M = R_2 - 2\ R_1$

$R_M = 2620\ \Omega - 2512\ \Omega$

$R_M = 108\ \Omega$

7. If R_M is small enough, it can be read directly with a digital voltmeter.

CONSTRUCTION OF A D.C. VOLTMETER

MATERIALS

VOM.
Multiplier resistor, R.
Basic meter movement ($I_{FS} = 1$ mA, $R_M \approx 100\ \Omega$).

PROCEDURE

1. Prior to completing the basic voltmeter circuit shown in Figure 10, determine maximum voltage V_{AB} that will be measured, the meter's internal resistance R_M, and the meter's full-scale current I_{FS}.

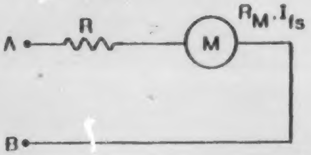


FIG. 10

2. Record the results of the following calculations in Data Table 2. In this circuit, the total resistance between A and B is —

$$R_t = R_M + R,$$

and the total current is the full scale meter current is —

$$I_t = I_{FS}.$$

From Ohm's Law, the voltage V_{AB} is given by —

$$V_{AB} = I_t R + I_t R_M = I_{FS} R + I_{FS} R_M.$$

From this equation, the multiplier resistance is —

$$R = \frac{V_{AB}}{I_{FS}} - R_M.$$

EXAMPLE CALCULATIONS

For V_{AB} = 10 volt full scale

$I_{FS} = 1\ \text{mA}$

$R_M = 100\ \Omega$

$$R = \frac{10\ \text{V}}{1\ \text{mA}} - 100\ \Omega = 9900\ \Omega$$

For V_{AB} = 100 volt full scale

$I_{FS} = 1\ \text{mA}$

$R_M = 100\ \Omega$

$$R = \frac{100\ \text{V}}{1\ \text{mA}} - 100\ \Omega = 99900\ \Omega$$

Determine necessary series resistance R, and construct meter circuit.

3. Measure voltage of an unknown source (maximum voltage V_{AB}) with meter constructed, and record in Data Table 2. The measured voltage is V_{AB} times the fraction of full scale deflection registered by the needle.
4. Measure the same voltage with the VOM, and record in Data Table 2.
5. Explain voltmeter operation.

CONSTRUCTION OF A D.C. AMMETER

MATERIALS

VOM.
Shunt resistor, R_s (resistance wire may be used).
Basic meter movement (I_{FS} = 1 mA, R_I = 100 Ω).

PROCEDURE

1. Determine maximum total current I_t to be measured.

2. From basic ammeter circuit depicted in Figure 11, the shunt resistance can be calculated as follows:

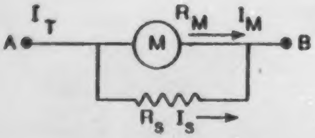


FIG. 11

V_M = Voltage across meter

V_s = Voltage across shunt

$$V_M = V_s$$

$$V_M = I_M R_M$$

$$V_s = I_s R_s$$

$$I_t = I_s + I_M$$

$$R_s = \frac{R_M I_M}{I_t - I_M}$$

Record results in Data Table 3.

EXAMPLE CALCULATION

Assume the maximum current to be measured is —

I_t = 100 mA (full-scale deflection)

R_M = 100 Ω

I_M = 1 mA

$$R_s = \frac{R_M I_M}{I_t - I_M}$$

$$R_s = \frac{(100\ \Omega)(1\ \text{mA})}{(100\ \text{mA} - 1\ \text{mA})}$$

$$R_s = 1.01\ \Omega$$

With such a shunt resistance in Figure 11, the meter movement would register full scale (100 mA), although only 1 mA passed through the meter-movement coil. The remaining 99 mA are carried by the shunt.

3. Determine and record necessary shunt resistance R_s, and construct meter circuit.

4. Measure unknown current with constructed meter (maximum current I_t) and record in Data Table 3. The unknown current is equal to I_t times the fractional full-scale deflection registered by the needle.

5. Measure the same current with the VOM and record in Data Table 3.

6. Explain any difference between current measured with constructed meter and that measured with VOM.

DATA TABLE 1: METER INTERNAL RESISTANCE

R_1 = ____________ Ω

R_2 = ____________ Ω

$R_M = R_2 - 2\,R_1$ = ____________ Ω

DATA TABLE 2: D.C. VOLTMETER

V_{AB} = ____________ V

I_{FS} = ____________ A

R_M = ____________ Ω

$R = \dfrac{V_{AB}}{I_{FS}} - R_M$ = ____________ Ω

Unknown voltage measured with constructed meter: ____________ V

Same voltage measured with VOM: ____________ V

DATA TABLE 3: D.C. AMMETER

I_t = ____________ mA

I_M = ____________ mA

R_M = ____________ Ω

$R_{\text{[illegible]}} = \dfrac{R_M I_M}{I_t - I_M}$ = ____________ Ω

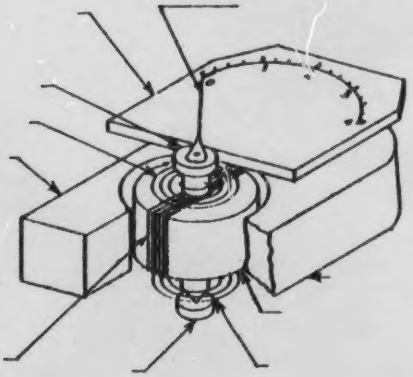
Unknown current measured with constructed meter: ____________ mA

Same current measured with VOM: ____________ mA

SELF CHECK

1. List three types of meter movements and an application of each.

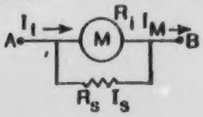
2. Identify the components of the adjoining meter movement.



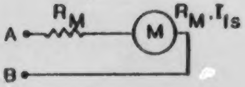
3. Explain how a stationary-magnet/moving-coil meter operates. Include a discussion of the meter movement as an energy convertor.

4. Correctly identify the following meter circuits.

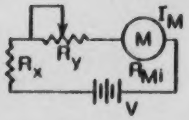
a.



b.



c.



5. Explain how the internal resistance of a meter movement can be determined.

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 10 T 1

AUTOMOBILE THERMOSTATS

THERMAL APPLICATION OF TRANSDUCERS

Technical Education Research Center – Southwest

TERC - SW

INTRODUCTION

Thermal expansion is employed in a variety of thermostats which are used for the monitoring and automatic control of temperature. A good example is the automobile water thermostat. As the water in the engine block becomes hot, thermal expansion in the thermostatic device opens a valve allowing the water to flow to the radiator. This keeps the engine from overheating.

In this module, the student will check the operation of an automobile water thermostat.

PREREQUISITES

Student should have completed Module 10-0, "Transducers."

OBJECTIVES

To complete this module, the student should be able to:

- Give a brief definition of a thermostat.
- Describe the use of thermal expansion in the operation of thermostats.
- Briefly explain the functional operation of the automobile thermostat.
- Describe what happens when an automobile thermostat fails to open or close.
- Given the appropriate equipment, determine the operating temperature of an automobile thermostat.

DISCUSSION

In this discussion, we shall define the term thermostat, describe how some different types of thermostats operate, and discuss their use in the automatic control of temperature. Particular emphasis will be placed on automobile thermostats.

Many types of thermostats employ the phenomenon of thermal expansion. The physical basis of thermal expansion has already been described (Module 1T3) with appropriate quantitative equations for the magnitude of expansion. To review briefly, the length of a sample of material changes when the temperature of the material changes. Most materials expand as temperature increases and contract as temperature decreases. A well-known application of thermal expansion involves the mercury thermometer. The length of the column of mercury in the thermometer increases as the temperature increases and this can be used as a sensitive indicator of temperature.

The physical phenomenon of thermal expansion can be used to sense the temperature of the environment and then used as a control to regulate that temperature. Devices that control the temperature in response to the input of a temperature sensor are called thermostats. Thermostats respond to a change in temperature and are used to actuate equipment such as furnaces or air conditioners. The thermostat operates in conjunction with a thermometer. A thermostat can be "preset" to a desired temperature level and subsequently act to control the temperature near a desired level.

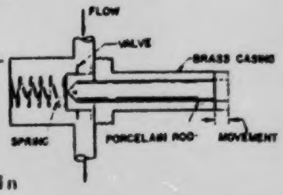

Fig. 1

The temperature sensing elements used in connection with thermostats often rely on thermal expansion. Two examples of temperature sensing elements that use this principle are shown in Figures 1 and 2. Figure 1 shows a tube type of temperature sensor. The brass tube contracts as the tube cools and pushes the porcelain rod to the left. This opens the valve, allowing hot gas or liquid to flow through the valve. When the temperature increases, the brass tube expands and pulls the porcelain rod to the right, closing the valve. A sample of an expansion calculation is shown in Example A.

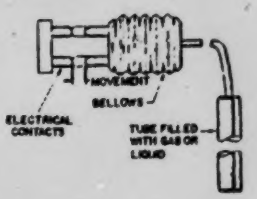

Fig. 2

Figure 2 shows a bellows type of sensor. The bellows is filled with a gas or liquid which expands and contracts as the temperature increases or decreases. As the temperature increases and the gas or liquid expands, the bellows expand and close the electrical contacts on the left. The closed circuit may be used to operate some piece of equipment. As the temperature increases and the gas or liquid contracts, the bellows will contract and the electrical contacts will be broken.

The thermostat is a transducer, according to the concepts described in Module 10-0. It provides an output signal (mechani-

EXAMPLE A : BRASS TUBE EXPANSION CALCULATION

Given: Thermostat shown in Figure 1.

Find: The change in length of a 25 cm long brass tube, in a furnace, when it undergoes a change in temperature from room temperature (20°C) to 200°C.

Solution: We use Equation 1 from Module 2T3:

$$L - L_o = L_o \alpha (T - T_o)$$

where

$L - L_o$ = change in length.
L_o = original length.
$T - T_o$ = change in temperature.
α = coefficient of linear thermal expansion.

From Table 1 in Module 2T3, $\alpha = 20.3 \times 10^{-6}/C^\circ$ for brass. Substituting into the equation the appropriate values:

$$L - L_o = 25 \times 20.3 \times 10^{-6} \times (200 - 20)$$

Therefore $\Delta L \cong 0.091$ cm.

Thus, the tube changes length by almost 1 mm, a motion large enough to activate a valve.

cal motion) in response to an input (temperature change), and in so doing it transforms thermal energy into mechanical energy.

The mechanical energy may be used to activate a device, like a valve, to provide feedback control of the temperature. For example, with reference to the device in Figure 1, when the temperature is lower than desired, the thermal contraction of the tube opens the valve and a hot fluid flows through the valve. This raises the temperature to the desired level, at which point thermal expansion of the tube reshuts the valve. Thus a thermostat is an important element in a system, allowing automatic monitoring of temperature and feedback control to keep the temperature at some desired value.

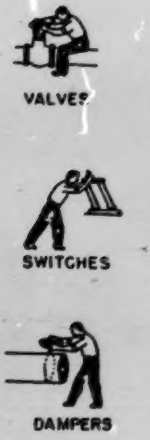

Fig. 3

Thermostats are used in many applications - for example, control of temperature in houses, office buildings, ovens, stoves, electric irons, refrigerators, freezers, and aircraft. Aircraft in particular have many thermostats for control of delicate instruments in a constantly changing temperature environment. Thermostats are used to open and close valves, switches, and dampers (Figure 3). By opening and closing a valve, the thermostat can control the flow of a fluid which is used for heating or cooling. By control of a switch, a thermostat can turn an electric motor on or off. By control of a damper, the thermostat can direct the flow of a heated or cooled gas to different positions.

A common example of the use of thermostats is found in the automobile water cooling system. Let us consider this thermostat in some detail. A thermostat controls the flow of the coolant in an automotive engine in order to keep the temperature of the engine within desired limits. First we describe the operation of an automotive cooling system, typical of most American-made cars (Figure 4). The cooling system of a modern automobile must remove large amounts of heat from the engine. The coolant most often used is a mixture of water and ethylene glycol. The latter is a chemical that may be mixed with water, both lowering its freezing point and raising its boiling point. Thus, ethylene glycol is commonly used as a summer coolant, and in areas where winter temperatures drop below the freezing point of water, as an antifreeze.

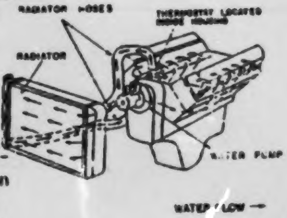

Fig. 4

The water pump circulates the coolant as indicated. The coolant flows into the engine block and circulates in water jackets around the engine cylinders. It leaves the engine near the front part of the block and passes into the thermostat housing. The thermostat controls a valve which can open or close in response to the thermpature of the water. When the water is at relatively low temperature, the valve is closed and the coolant will be recirculated within the engine itself, bypassing the radiator. As the engine heats up and the temperature of the water in the engine increases, the valve opens and part of the coolant passes through the upper radiator hose into the raditor. The radiator is a heat exchanger which contains a number of thin water tubes each of which has thin metal fins on the outside. The water is cooled by radiation and by the flow of air past the radiator (convection).

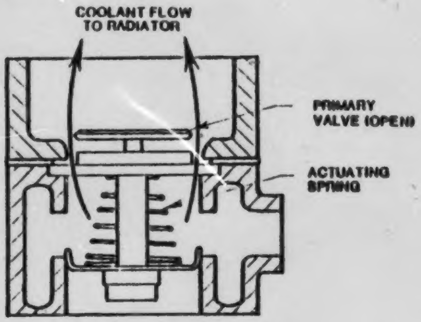

Fig. 5

In this way, the thermostatic valve can adjust the cooling capacity of the cooling system, according to weather conditions and to the heat load generated by the engine. The thermostat might be designed as indicated (Figure 5). When the water in the engine is cold, the actuating spring in the thermostat holds the valve closed and the water flow is shut off.

Since the water does not circulate through the radiator, it becomes hotter as the engine runs. When the desired temperature in the engine is reached, the thermostat expands and pushes the valve off its seat so that water is able to move through the upper radiator hose into the radiator.

Improper operation of the thermostat can adversely affect the car's cooling system. If the thermostat does not close completely when cold, the engine will warm up very slowly, or perhaps not at all. This will impair the performance of the heater during cold weather. Thus, an engine that does not get warm enough often indicates a faulty thermostat.

On the other hand if the thermostat does not open properly at the desired temperature, water will not circulate through the radiator and the heat of the engine will not be removed. This can lead to overheating and possible damage to the engine. Overheating of the engine may indicate a faulty thermostat.

An automobile water thermostat is usually stamped with a temperature range. Typical values are in the range of 160° - 190°F. The two temperatures correspond to the fully closed and fully open conditions of the valve. Thermostats with lower values of opening temperature may be used under hotter conditions, allowing coolant flow to the radiator sooner. Thermostats with higher values may be used in colder conditions to allow faster engine warmup and better heater operation. Some car owners change their thermostats if there is a severe temperature change in summer and winter.

LABORATORY

MATERIALS

Automotive thermostat.
Stove or bunsen burner.
Beaker of water.
Thermometer.
Set of feeler gages.
Clamps and stands as needed to support beaker.
Socket wrench set (optional).
Gasket for thermostat housing (optional).
Gasket seal compound (optional).

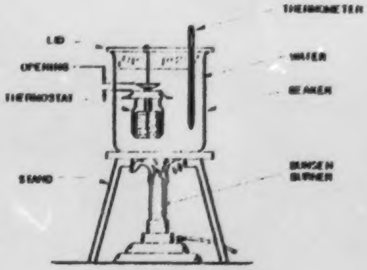

Fig. 6

PROCEDURE

As part of the exercise, the student will check the operation of the water thermostat from his own automobile.

1. From the manufacturer's manual, obtain the details of the thermostat needed for the car model.
2. When the engine is cool, drain water from the cooling system so that the water level is below the level of the thermostat.
3. Remove the upper radiator hose from the thermostat housing and remove thermostat housing bolts. Note the orientation of the thermostat when removing the housing and thermostat to make sure it is reinstalled correctly later.
4. Inspect the thermostat visually to make sure that the thermostat valve is closed at room temperature.
5. Immerse the thermostat in the beaker of water. (Do not touch sides of beaker.)
6. Heat the water and stir it to ensure uniform temperature (Figure 6). Measure the water temperature with a thermometer.
7. The thermostat should begin to open slightly at the lower temperature. Insert a 0.001 inch feeler gage into the opening. Measure the temperature when the thermostat opens enough to admit the feeler gage. The feeler gage should enter the valve opening freely at a temperature just above the lower rated value of the thermostat.
8. Continue heating the water to approximately the upper temperature range. The thermostat valve should be fully open at this temperature.
9. When reinstalling the thermostat, use a new gasket and coat the gasket with a gasket sealing compound to ensure a leak-proof seal.

10. Reinstall thermostat and housing and retighten housing bolts.
11. Reattach upper radiator hose.
12. Refill radiator to proper level and run engine to check if thermostat is operating properly.

SELF CHECK

1. Define thermostat.
2. Explain how the phenomenon of thermal expansion is used in thermostats.
3. Describe the operation of an automobile thermostat.
4. Describe what happens when an automobile thermostat fails to open or close.
5. What two automobile malfunctions may indicate a faulty thermostat?

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 10 T 2

BIMETALLIC STRIPS

THERMAL APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

A bimetallic strip is constructed of two dissilimar metals having different coefficients of linear expansion and bonded together in intimate contact along their long dimension. When the strips are heated, the metal with the higher coefficient of expansion expands more than the other metal, causing the strip to bend. Because the amount of bending is proportional to the temperature change, bimetallic strips are convenient devices for use in thermostats and oven thermometers. The bimetallic strip can be considered a transducer, since the thermal energy absorbed by the strip is converted partially into the potential energy of deformation stored in the bent strip.

This module introduces the design and operation of bimetallic strips. In the laboratory, the student will construct a simple bimetallic strip; will measure the motion of the end of the strip as it is heated; and will use it to construct a control circuit.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Describe how a bimetallic strip operates.
- List at least two applications of bimetallic strips.
- Name the combination of metals often used in bimetallic strips.
- Given the length, thickness, temperature, and deflection of a straight bimetallic strip, calculate the required difference in coefficients of expansion of the two metals.
- Given the radius, thickness, length, coefficient, and distance of deflection of a spiral bimetallic strip, calculate the temperature increase.

- Given the appropriate equipment, construct a simple bimetallic strip, measure its deflection when heated, and assemble a control circuit.

DISCUSSION

Bimetallic strips are constructed of two different metals fastened together along their length. The construction is indicated in Figure 1. Figure 1a shows a piece of bimetallic strip made of two equal lengths of two different metals. The two metals exhibit different values for their coefficients of linear expansion. Assume that metal A has a higher value for its coefficient of linear thermal expansion than metal B. The strip is formed at room temperature by bonding or fastening the two pieces of metal together.

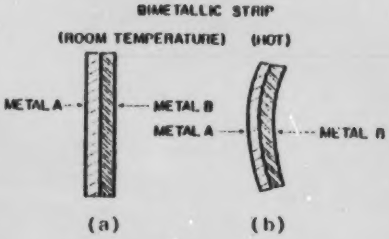


FIG. 1

In order to manufacture bimetallic strips in large quantity, strips of two separate metals are fed into a welding station and spot welded together along their length. At room temperature the strip is, of course, straight.

Now, what happens when the strip is heated? The answer is found in Figure 1b. Both metals expand as the temperature rises, but metal A expands more. Since the two metals are bonded together, and since metal A cannot simply slip past metal B by expanding, a force is generated and bends the strip as shown in Figure 1b. The subsequent bending allows metal A to become slightly longer, while remaining attached to metal B along its length. Thermally-generated energy and forces of expansion are responsible for the bending.

The two metals used in a bimetallic strip should have values of coefficient of linear expansion (Table 1) that differ as much as possible; for if the two metals had equal values of the coefficient, they would expand equally, and there would be no bending. The amount of bending increases as the difference between the coefficients increases.

TABLE 1. PROPERTIES OF VARIOUS MATERIALS

Material	Linear Coefficient of Thermal Expansion (Per Degree C)	Modulus of Elasticity ($Dyne/cm^2$)
Aluminum (commercially pure)	23.5×10^{-6}	6.9×10^{11}
Brass (yellow, 65% Cu, 35% Zn)	20.3×10^{-6}	10.3×10^{11}

Copper (commercially pure)	16.5×10^{-6}	12.8×10^{11}
Glass		
Borosilicate	6.2×10^{-6}	---
Pyrex	$(3.1 - 3.5) \times 10^{-6}$	---
Soda-lime	$(7.5 - 9.2) \times 10^{-6}$	---
Invar (64% Fe, 36% Ni	1.2×10^{-6}	14.8×10^{11}
Kovar (54% Fe, 28% Ni, 18% Co)	5.9×10^{-6}	13.8×10^{11}
Quartz, fused	0.5×10^{-6}	7.2×10^{11}
Stainless steel (17-20% Cr, 8-11% Ni)	9.6×10^{-6}	19.3×10^{11}
Titanium (commercially pure)	8.5×10^{-6}	11.6×10^{11}
Tungsten (commercially pure)	4.3×10^{-6}	34.5×10^{11}

The largest value of the difference can be obtained if one metal has a high value for the coefficient of linear expansion and the other metal has a value near zero. The metal "Invar" has a near-zero value for its coefficient. Invar is an alloy, consisting of 64% iron and 36% nickel. Its coefficient of linear expansion is about 1.2×10^{-6} per C°, a value much lower than that of most other metals. Thus, invar often is used as the metal with low expansion characteristics.

Brass (65% copper, 35% zinc) is a metal with a reasonably high value of thermal expansion coefficient (about 20.3×10^{-6} C°), about 20 times greater than invar. Although this is not the highest known value, brass is relatively inexpensive. Thus, the combination of invar-brass offers a relatively high value for the difference in thermal expansion coefficients; this combination often is used in practical bimetallic strips.

Choice of metals depends upon the temperature range in which the device is to be used. The combination of brass and invar frequently is used for applications in which the expected temperature range centers around room temperature. The coefficients of thermal expansion change with temperature, however, so that no one combination of metals is suitable for all temperature ranges. For measurements in high temperature ranges, alloys consisting of 20-24% nickel, 2-4% chromium, and the remainder of iron have been useful.

With proper choice of metals, bimetallic devices have been constructed to cover a temperature range from -300°F up to 1000°F.

Construction of bimetallic strips can take a variety of forms, as seen in the straight strip (Figure 1). Although the operation of the device is understood readily with reference to the straight strip, other configurations probably are used more often in practical devices. Spiral construction (Figure 2) often is used in practical temperature-measuring systems, as the spiral will either unwind or coil more tightly as the temperature changes, which causes the motion of the end of the spiral. The deflection of the end of the spiral is denoted as x in Figure 2.

The stress pattern generated in the bimetallic strip as it is heated is shown in Figure 3. Metal with the higher coefficient of linear expansion is the bottom one. Ordinarily, when it is heated, it will expand according to Equation 1.

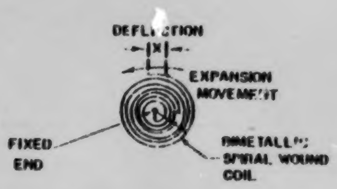


FIG. 2

$$\ell_2 - \ell_1 = \alpha \ell_1 (T_2 - T_1) \qquad (1)$$

where

ℓ_1 = length of metal sample at some lower temperature.
ℓ_2 = length of metal sample at some higher temperature.
α = coefficient of linear expansion for sample.
T_1 = lower temperature.
T_2 = higher temperature.

Equation 1 gives the maximum elongation of an unbonded piece of metal. However, when a piece of this same metal is bonded to some other metal having a lower expansion coefficient, it is constrained from expanding linearly as much as the above relationship would require. This constraint leads to compressive forces being generated in that metal at the interface between the two metals. Similarly, the low-expansion metal at the top is being stretched by its contact with the high-expansion metal. This process leads to tension (i.e., forces that tend to stretch the material) at the interface. The combination of these two forces causes the strip to bend, so that it is concave upwards. After bending, the top of the strip becomes slightly compressed and the bottom slightly stretched, leading to the pattern of compression and tensile forces illustrated in Figure 3.

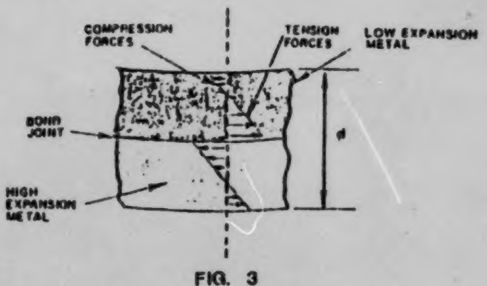


FIG. 3

Consider the deflection that is experienced by a bimetallic strip clamped at one end. The geometry is illustrated in Figure 4; length of strip is denoted by ℓ and its thickness by d. The strip is assumed to be straight at some value of temperature T_1. When the temperature is raised to T_2, the strip will bend (Figure 4); and the end of the strip will move by an amount x. Deflection is given by Equation 2.

$$x = 3\,(\alpha_A - \alpha_B)(T_2 - T_1)\ell^2/4d \qquad (2)$$

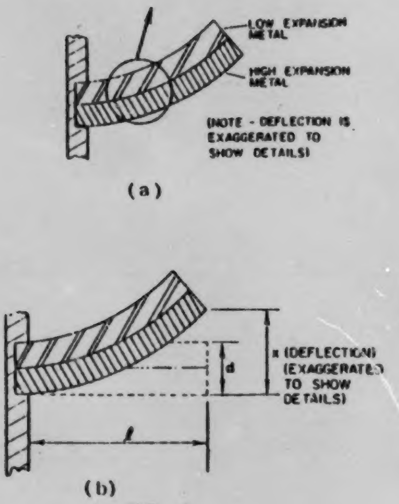

LOW EXPANSION METAL
HIGH EXPANSION METAL
(NOTE - DEFLECTION IS EXAGGERATED TO SHOW DETAILS)
(a)
x (DEFLECTION) (EXAGGERATED TO SHOW DETAILS)
d
ℓ
(b)

FIG. 4

where

x = deflection of end of strip.
α_A = coefficient of thermal expansion of metal A.
α_B = coefficient of thermal expansion of metal B.
T_1 = lower temperature at which strip is straight.
T_2 = higher temperature, which produces amount of deflection x.
ℓ = length of strip.
d = thickness of strip.

Equation 2 is employed in the solving of a problem in Example A.

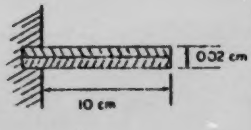
The deflection of a straight strip, therefore, is directly proportional to the change in temperature and to the square of the length of the strip, and inversely proportional to its thickness. The fact that the deflection is proportional to the temperature change is a valuable feature for the practical use of bimetallic strips, as this simplifies its calibration. The device can be calibrated at two known temperatures, and a linear response over the entire temperature scale is obtained, as long as α_A and α_B vary negligibly with temperature over this range.

In practice, the linear response of the bimetallic strip extends over a limited temperature range. For an application involving measurements over a wide range of temperatures, make sure that the materials of the chosen device exhibit linearity over the desired range of temperatures (Example A).

EXAMPLE A: BIMETALLIC STRIP DEFLECTION

Given: A straight bimetallic strip of brass and invar is clamped at one end and is 10 cm long and 0.02 cm thick.

Find: Deflection of end when strip temperature increases by 10C°.



Solution: Refer to Table 1: For brass, the linear coefficient of thermal expansion is 20.3×10^{-6} per C° and for invar it is 1.2×10^{-6} per C°.

Use Equation 2:

$$x = 3(\alpha_A - \alpha_B)(T_2 - T_1)\ell^2/4d$$

$$= 3(20.3 \times 10^{-6} - 1.2 \times 10^{-6})(10^2)10/(4 \times 0.02)$$

$$x = 0.72 \text{ cm}$$

For a spiral (Figure 2), the deflection of the end of the spiral is given by Equation 3.

$$x = 9\,(\alpha_A - \alpha_B)(T_2 - T_1)r\ell/4d \qquad (3)$$

where

r = radius of spiral.
ℓ = extended length of strip.

Equation 3 is valid only under conditions in which the two metals have nearly equal moduli of elasticity (Table 1). Thus, in the case of a spiral, the deflection of the end again is linearly proportional to the temperature change.

An important use of bimetal strips is in thermostats. Bimetal strips are found in many thermostats used for control of temperature in the home. If the thermostat cover is removed, the strip (often a spiral) can be viewed. As the temperature in the home changes, the motion of the strip is used to open and to close a switch, which turns the heating/cooling system on and off. Thus, the bimetallic strip is an important element in a common house control system.

Oven thermometers also use bimetallic strips and usually have a round face, to accommodate a spiral strip. Motion of the bimetallic strip moves a pointer that indicates the oven temperature.

SUMMARY

The bimetallic strip is a good example of a practical application of the expansion of materials. It consists of two strips of metal fastened together in such a manner that at some temperature they are straight. The two strips of metal have different coefficients of expansion. If the strip is heated, it will bend in a curve; the amount of bending produced will be determined by the change in temperature experienced by the strip. Bimetallic strips, therefore, are frequently used in thermostats.

BIMETALLIC STRIP DEMONSTRATION

MATERIALS

Brass and zinc strips (other metal strips can be used, as available).
Metal snips.
Pliers.
Vise.
Piece of thin bell wire.
Ruler.
Candle and matches.
Oven thermometer.
Screwdriver.
Hammer, nail, and tacks.
Board (6" x 6" x 1/2").
Battery (1 1/2 volt).
Bulb (1 1/2 volt) and holder.
Wire and clips as needed.
Hair dryer or substitute.
Epoxy.

PROCEDURE

1. Construct a simple bimetallic strip as follows:

   (a) Cut off equal lengths of brass and zinc strips, about 12 inches each. Smooth to straighten. The brass and zinc are suggested because of easy availability; strips of other metals can be substituted as available.

   (b) Clamp the two strips together, and make slits in strips with metal snips (Figure 5). Bend flaps over to fasten two strips together. Tighten flaps with pliers to hold securely. Make as many flaps as possible.

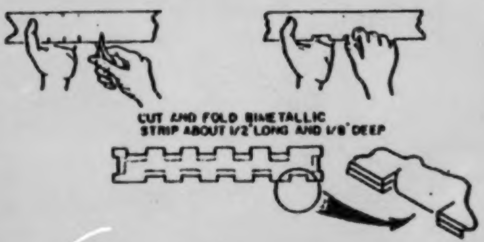

CUT AND FOLD BIMETALLIC
STRIP ABOUT 1/2" LONG AND 1/8" DEEP

FIG. 5

2. Observe the deflection of strip as it is heated.

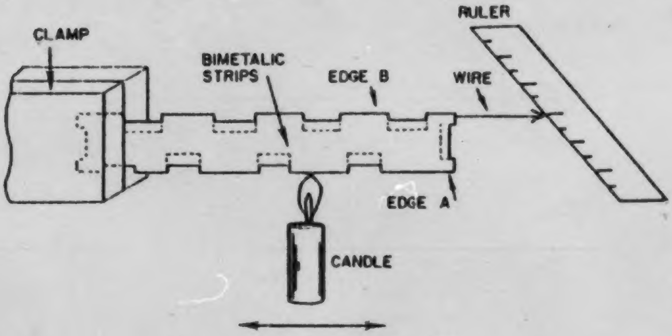


FIG. 6

(a) Set up apparatus (Figure 6). Firmly clamp one end of strip. Insert a piece of thin wire into flap at free end of strip to be used as a pointer. Place a ruler at right angles to strip with end of wire near ruler.

(b) Light candle and move flame back and forth under strip on edge A.

(c) Observe motion of strip.

(d) Remove flame. Does wire return to its original position?

(e) Reverse strip edge A for edge B, and repeat steps b and c. Which direction does pointer move now? Why?

3. Disassemble an inexpensive oven thermometer, and use the bimetallic spiral strip for control of a light bulb.

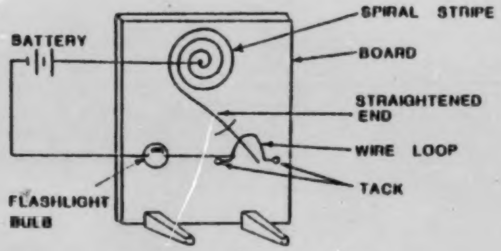


FIG. 7

(a) Pry apart an inexpensive oven thermometer with a screwdriver. Remove spiral bimetallic strip.

(b) Straighten end of bimetallic strip (about last three inches). Set up apparatus shown (Figure 7). Make a nail hole in board, and firmly insert spindle from strip into hole and epoxy it to board so that it does not turn. Mount a wire loop with tacks with straightened end of spiral through loop. Strip should be about 1/8" from loop. Make electrical connections as shown, with connections from battery to spindle of spiral and from the bulb to wire loop.

(c) Heat spiral with hair dryer. Does bulb light? (If it does not light quickly, reduce gap between loop and end of strip.)

(d) Remove hair dryer. Does light bulb go out? How does this experiment demonstrate use of a bimetallic strip for control applications?

SELF CHECK

1. Describe operation of bimetallic strips.

2. Name at least two applications for bimetallic strips.

3. Name a combination of metals often used in bimetallic strips.

4. If a straight bimetallic strip of length 18 cm and of thickness 0.1 cm is clamped at one end heated by 15C°, what is the required difference in the coefficients of expansion of metals, for an observed motion of free end of 0.23 cm?

5. A spiral bimetallic strip of radius 5 cm, thickness 0.05 cm and length 25 cm, is made of metals with coefficients of thermal expansion equal to 17×10^{-6} and 5×10^{-6} per C°. When it is heated, the end deflects through a distance 0.675 cm. What was the increase of temperature?

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 10 T 3

TEMPERATURE MEASURING DEVICES

THERMAL APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Temperature is a measure of the average kinetic energy of the molecules of a substance. The increased motions of molecules caused by the absorption of heat energy is difficult to measure directly, but these microscopic motions cause other physical quantities that can be measured to change. Thus, measurements of physical quantities like volume, pressure, mechanical distortion, voltage, and resistance can be used as an indication of temperature. Ultimately, temperature in a particular range must be defined in terms of the measurement of such a quantity. A temperature-measuring device can be viewed as one which transforms molecular kinetic energy into a form that is more easily accessible to the experimenter. This module introduces the theory and applications of such devices. In the laboratory, the student will perform temperature measurements with a thermocouple and with a thermistor.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Sketch a fluid-filled thermometric system, label the pointer, pressure-sensitive element, scale, capillary tube, and fluid-filled bulb; and describe in one or two sentences the friction of each.
- Describe in a short paragraph the theory and operation of a bimetallic strip, and indicate how it can be used in a practical situation.
- Draw, label, and briefly describe the operation of the five key parts of a thermocouple.
- Given one of the three variables of a thermocouple, including

its abbreviation, symbol, or color code, identify the two conductors and the other two variables.

- Describe the use of the thermopile in a temperature-sensing system.
- Discuss in two or three sentences why and how a thermistor is used to measure small temperature variations.
- Given the appropriate equipment, measure the temperature of a liquid with a thermocouple and with a thermistor, and plot the temperature measured against their output voltage.

FLUID-FILLED DEVICES

A common temperature-measurement technique makes use of fluid-thermal systems. When a closed system is filled with a fluid and sealed, an increase in temperature causes the fluid to expand. When the fluid expands, the motion is transmitted to a pointer or indicator by means of a link and lever system.

Fluid-filled thermal systems are categorized by the type of fluid used. The fluid may be a liquid or a gas, or in the case of mercury, a fluid metal.

All such measuring devices consist of a bulb (reservoir for the fluid), a pressure-sensitive element and a capillary tube joining the two. An example of such a device is shown in Figure 1.

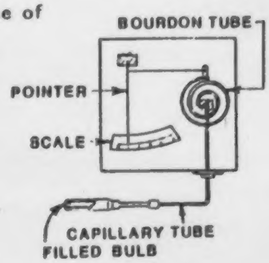


FIG . 1

Liquid and mercury systems typically operate on a volumetric change of the filled material with a change in temperature, while gas systems operate on a pressure change with temperature.

The most common type of fluid system is the glass thermometer, which uses either mercury of alcohol as the fluid. Temperature changes cause a change in the volume of the fluid, and the movement of the liquid along a thin cylinder of constant diameter permits the change in volume to be registered as a change in length. Thus, an empirically-constructed linear scale along the cylinder easily can be calibrated in terms of temperature.

More sophisticated systems employ a transducer that converts the movement caused by volumetric or pressure changes to a scaled pneumatic or electronic signal. This signal, in turn, is transmitted to a receiving instrument, where the signal response is interpreted as a temperature. These temperature transmitters are used in industry for control purposes; on motor vehicles for measurement of engine oil temperature; and also as temperature control devices in the home.

BIMETALLIC STRIPS

A bimetallic strip is constructed by the joining together of two metals that have different rates of thermal expansion. When the device is heated, the unequal thermal expansion of the two metals causes a bending of the strip, because one metal expands at a greater rate than the other. Figure 2 shows how a temperature change is transformed to mechanical motion in the bimetallic strip. Bimetallic strips of this construction are used most commonly in single-temperature control circuits to

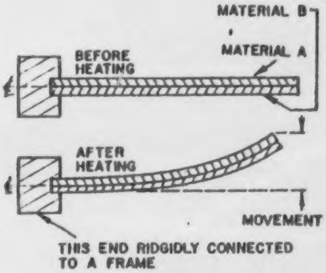


FIG . 2

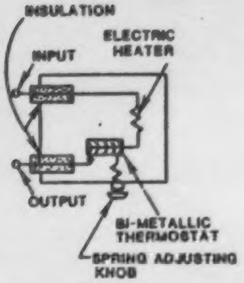
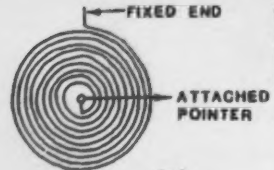


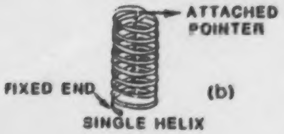
FIG. 3

make or to break an electrical contact that produces corresponding fluctuations in temperature. Figure 3 illustrates one such device. When the temperature of the unit increases to a point at which the thermal expansion of the bimetallic strip is great enough to overcome the spring tension, the contact opens, breaking the electrical circuit to the heater. As the unit cools down, the bimetallic strip returns to its original shape and again closes the heater circuit. The cycle continues to repeat and, therefore, to control temperature in a given enclosure.

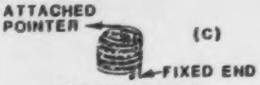
In applications where it is desirable to incorporate the response of a bimetallic strip to provide temperature measurement instead of control, the bimetal element is wound into the form of a spiral or helix (Figure 4). The response of movement of the strip with temperature change is increased in this way and can be made linear over a range of temperature change of about 400°F. For temperatures greater than 400°F, nonlinear scales can be empirically constructed



SPIRAL (a)



(b)
SINGLE HELIX



(c)
MULTIPLE HELIX

FIG. 4

THERMOCOUPLES

Measurement of temperatures by their electrical effect is used often in applications where it is necessary to take measurements in remote or hazardous locations. When a thermocouple is used to measure temperature, the read-out device can be in a central control room thousands of feet or more from the point of measurement. The voltage produced by the temperature differential sensed in the thermocouple can be transmitted easily over electrical cables.

Two dissimilar metals joined together at one end produce a small voltage across the open ends if a temperature difference exists between the junction and the open ends. The open ends are connected to a sensitive voltage-measuring device, such as a millivoltmeter or a potentiometer (Figure 5).

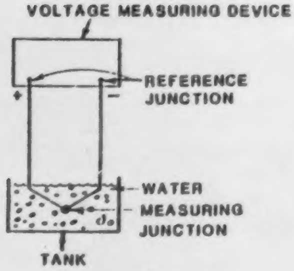


FIG. 5

The point at which the wires are connected is called the "measuring junction." The points at which the wires are connected to a voltage-measuring device are called "reference junctions." When the temperature of the measuring and reference junctions are equal, no voltages will be developed at the voltmeter. When the temperature of the measuring junction is elevated above that of the reference junction, a voltage will be generated with some polarity (plus-or-minus). When the measuring-junction temperature is decreased below that of the reference junction, the voltage developed at the voltmeter reverses polarity. As the temperature difference between the two junctions increase, the voltage at the measuring junction increases.

Table 1 lists common thermocouple abbreviations, symbols, conductor polarities, and wire color codes; Table 2 provides thermocouple data for design use.

TABLE 1. COMMON THERMOCOUPLE ABBREVIATIONS, SYMBOLS, CONDUCTOR POLARITY AND WIRE COLOR CODE

Abbreviation Used in Table 2	Symbol	Color	Conductor Polarity		Color
			Positive (+)	Negative (-)	
I/C	J	White	Iron	Constantan	Red
C/A	K	Yellow	Chromel	Alumel	Red
C/C	T	Blue	Copper	Constantan	Red
CR/C	E	Yellow	Chromel	Constantan	Red

Thermocouple calibration tables relate millivolts generated by the thermocouple to the temperature generated by the thermocouple to the temperature difference between the two junctions. Such tables are compiled from test data obtained when the reference-junction temperature is fixed, when the measuring-junction temperature is varied, and when the voltage generated by the thermocouple is measured precisely. Calibration tables often are based on constant reference-junction temperatures of 32°F (0°C), 75°F or 25°C. With the help of these tables, a thermocouple, and a millivoltmeter, temperatures can be determined accurately. Example A illustrates the use of Table 2.

EXAMPLE A: SELECTION OF MEASURING-JUNCTION TEMPERATURE

Given: An iron-constantan (type J) thermocuple has a reference-junction temperature of 75°F and a millivolt value of 3.54 mV.

Find: Temperature of measuring junction.

Solution: Notice that the reference junction temperature for Table 2 is 75°F. At 75°F, the voltage developed is 0.00. From the thermocouple calibration, Table 2, under the I/C type J for iron-constantan, a mV value of 3.54 corresponds to 195°F, the temperature of the measuring junction.

TABLE 2 . PARTIAL THERMOCOUPLE DATA

0 To 400°F

F	C/C T	I/C J	I/C Y	CR/C E	C/A K
0	-1.61	-2.11	-2.18	-2.45	-1.63
5	-1.51	-1.97	--	--	-1.53
10	-1.41	-1.83	-1.89	-2.14	-1.42
15	-1.30	-1.70	--	--	-1.32
20	-1.20	-1.56	-1.61	-1.82	-1.21
25	-1.09	-1.42	--	--	-1.10
30	-0.99	-1.28	-1.32	-1.50	-0.99
35	-0.88	-1.14	--	--	0.88
40	-0.77	-1.00	-1.03	-1.17	-0.77
45	-0.66	-0.86	--	--	-0.66
50	-0.56	-0.72	-0.74	-0.84	-0.55
55	-0.45	-0.57	--	--	-0.44
60	-0.34	-0.43	-0.44	-0.51	-0.33
65	-0.22	-0.29	--	--	-0.22
70	-0.11	-0.15	-0.15	-0.17	-0.11
75	0.00	0.00	0.00	0.00	0.00
80	0.11	0.14	0.15	0.16	0.11
85	0.23	0.29	--	--	0.23
90	0.34	0.43	0.44	0.50	0.34
95	0.46	0.58	--	--	0.45
100	0.57	0.72	0.74	0.84	0.57
105	0.69	0.87	--	--	0.68
110	0.81	1.01	1.04	1.19	0.79
115	0.93	1.16	--	--	0.91
120	1.04	1.30	1.34	1.54	1.02
125	1.16	1.45	--	--	1.14
130	1.28	1.60	1.64	1.89	1.25
135	1.40	1.75	--	--	1.37
140	1.52	1.89	1.94	2.25	1.48
145	1.65	2.04	--	--	1.60
150	1.77	2.19	2.24	2.61	1.71
155	1.89	2.34	--	--	1.83
160	2.01	2.49	2.55	2.97	1.94
165	2.14	2.64	--	--	2.06
170	2.26	2.79	2.85	3.34	2.17
175	2.39	2.94	--	--	2.29
180	2.51	3.09	3.16	3.70	2.41
185	2.64	3.24	--	--	2.52
190	2.77	3.39	3.46	4.07	2.64
195	2.90	3.54	--	--	2.75
200	3.02	3.69	3.77	4.44	2.87
205	3.15	3.84	--	--	2.99
210	3.28	3.98	4.08	4.82	3.10
215	3.41	4.14	--	--	3.22
220	3.54	4.29	4.38	5.19	3.33
225	3.67	4.44	--	--	3.45
230	3.81	4.59	4.69	5.57	3.56
235	3.94	4.74	--	--	3.68
240	4.07	4.89	5.00	5.95	3.79
245	4.20	5.05	--	--	3.91
250	4.34	5.20	5.31	6.33	4.02
255	4.47	5.35	--	--	4.13
260	4.61	5.50	5.62	6.72	4.25
265	4.74	5.65	--	--	4.36
270	4.88	5.81	5.93	7.11	4.47
275	5.01	5.96	--	--	4.58
280	5.15	6.11	6.24	7.50	4.70
285	5.29	6.26	--	--	4.81
290	5.43	6.42	6.55	7.89	4.92
295	5.56	6.57	--	--	5.03
300	5.70	6.72	6.86	8.28	5.14
305	5.84	6.88	--	--	5.25
310	5.98	7.03	7.17	8.68	5.36

The voltage generated by a thermocouple is a function of the difference in temperature between the two junctions. A change in temperature of either junction causes a change in millivolt reading. The necessity arises, therefore, to ensure that the thermocouple output is caused only by a temperature variation at the measuring junction. This precaution can be accomplished when the reference-junction temperature is held at a constant value and when the millivolt value at that temperature is subtracted from the millivolt value read on the voltmeter. The difference in millivolts then is converted to temperature in the table. Example B illustrates this method. A practical procedure involves the use of a thermocouple table referenced to 32°F (0°C). The reference junction then may be placed in ice water, and the thermocouple output converted directly to temperature from the table (Figure 6). The millivolt value of the reference-junction temperature need not be subtracted, because it is equal to zero at the reference temperature.

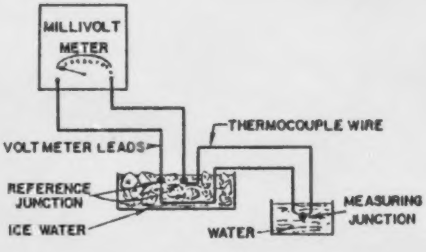


FIG . 6

EXAMPLE B : CALCULATION OF THERMOCOUPLE OUTPUT

Given: For an iron-constantan (type J) thermocouple, the measuring-junction temperature T_2 is 300°F and the reference-junction temperature T_1 is 100°F.

Find: Voltage generated by the thermocouple.

Solution: Remember that the thermocouple output is a function of the temperature difference between the two junctions.

From calibration Table 2, under the I/C type J column, 300°F corresponds to 6.72 mV, and 100°F to 0.72 mV. The difference is (6.72 - 0.72) = 6.00 mV. Thus, 6.00 mV is the thermocouple output.

THERMOPILE

When two or more thermocouples are connected in series, the voltage from the individual thermocouples add to produce a total voltage that is easier to measure and that can be used for control circuits. Figure 7 shows such an arrangement, giving a voltage five times as great as that measured with a single thermocouple. This arrangement is called a thermopile and can be used to measure small temperature differences.

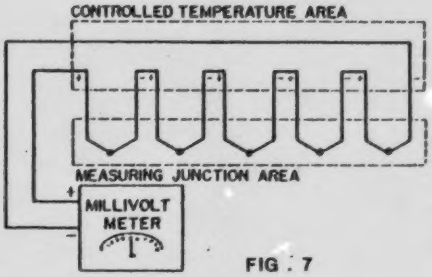


FIG . 7

THERMISTOR

Some electrical components change resistance with temperature to such a degree that measurement of resistance can be used as a means of determining very small temperature variations. Thermistors and elements called resistance-temperature devices are such components, which are used to measure temperature when connected to a bridge circuit. For example, the Wheatstone bridge circuit can be used to make accurate measurements of resistance (Figure 8).

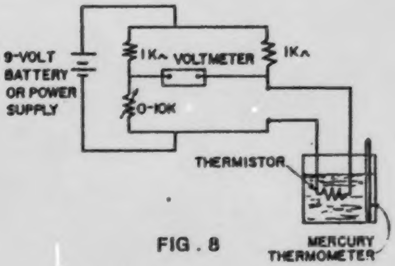


FIG . 8

SUMMARY

Four methods of temperature measurements have been discussed:

- Fluid thermal systems.
- Bimetallic strip.
- Thermocouple and thermopile.
- Thermistor.

Fluid thermal and bimetallic strips are used in home thermostats for measurement and control and in fail-safe systems for gas-fired furnaces and hot water heaters.

Thermocouples are used in applications in which an electrical signal is convenient for temperature measurement and in which transmission of temperature information over a distance is desired. Thermistors and other resistance devices are used when high sensitivity is required.

LABORATORY

THERMOCOUPLE TEMPERATURE MEASUREMENT

MATERIALS

Thermocouple wire (type J or copper-constantan).
Mercury thermometer.
Millivoltmeter.
Beaker.
Bunsen burner and stand.
Graph paper.

Note: Thermocouple wire, thermocouple calibration tables, read-out devices, and other thermocouple application devices are available from the Thermo Electric Company, Saddle Brook, New Jersey.

PROCEDURE

This experiment involves the construction of a calibration curve for a thermocouple.

1. Construct a thermocouple by twisting two ends of thermocouple wire together and connecting other ends to a millivoltmeter. Place twisted end in a beaker of cold water (Figure 9). Measure water temperature with mercury thermometer, and record temperature and millivolt value in Data Table 1.

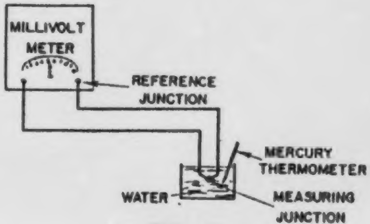


FIG . 9

2. Elevate temperature of water in approximately five-degree increments, and record each thermometer temperature and its corresponding millivolt reading in Data Table 1. Reference junction should be held constant, at room temperature.

3. Note condition when temperature of measuring junction and reference junctions are equal (that is, at room temperature). What is the reading on the millivoltmeter? What happens when the measuring junction temperature is higher than reference junction temperature? What happens when measuring junction temperature is lower than the reference junction temperature?

4. Plot temperature versus millivolt on linear graph paper.

Is the plot linear? Could it be used for temperature measurement?

THERMISTER TEMPERATURE MEASUREMENT

MATERIALS

Two 1000 ohm resistors.
One 0-10,000 ohm variable resistor.
One 9-volt battery or power supply.
One voltohmmeter.
One thermistor with resistance of about 5000 ohms at 25°C, available from Yellow Spring Instrument Company, Yellow Springs, Ohio (or equal supplier).
One mercury thermometer.
Graph paper.
Crushed ice (1 cup).
Bunsen burner and stand.

PROCEDURE

The following procedure is designed to measure the temperature of a substance over a wide range using a thermistor, and to make a plot of temperature versus voltage.

1. Assemble the circuit shown (Figure 8).

2. With thermistor at room temperature, vary the variable resistor until bridge is balanced; that is, until voltmeter reads essentially zero volts. Do not change variable resistance throughout remainder of the experiment.

3. Change temperature in 5°F increments above and below ambient for about 100° range. This process can be accomplished by adding bits of ice (cooling) and with a bunsen burner (heating).

4. Using mercury thermometer as a standard, record in Data Table 2 temperature and corresponding voltage indicated by Wheatstone bridge at each step.

5. Plot temperature values against corresponding voltages on linear graph paper. This is a temperature-calibration curve. It can be used for precise temperature measurements.

6. Is the temperature calibration curve linear? Compare linearity,

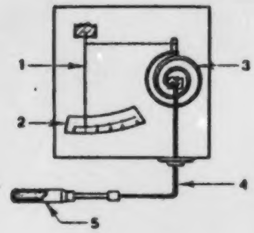
accuracy, and sensitivity with the thermocouple method. How could the sensitivity of this temperature-measuring system be improved?

DATA TABLE 1			
Temperature (In 5°F Increments)	Millivolt Value (Thermocouple Output)	Temperature (In 5° Increments)	Millivolt Value (Thermocouple Output)

DATA TABLE 2			
Temperature (In 5°F Increments)	Voltage (From Wheatstone Bridge	Temperature (In 5°F Increments)	Voltage (From Wheatstone Bridge)

SELF CHECK

1. Label the parts of this fluid-filled thermal system and describe the functions of each part.



1 ____________________
____

2 ____________________
____

3 ____________________
____

4 ____________________
____

5 ____________________
____

2. Briefly describe how a bimetallic strip can be used to control a thermostat.

3. Give a one- or two-sentence description of the function of the parts of a thermocouple, including the voltage measuring device, reference junctions, water, measuring junction, and tank.

4. Name the conductors, the abbreviation, and the color code for a thermocouple with a "T" symbol.

5. In one or two sentences, describe the use of a thermopile in a temperature-sensing system.

6. Describe in two or three sentences what happens to a thermistor when subjected to a temperature change.

REFERENCES

Anderson, Norman A. Instrumentation for Process Measurement and Control. 2nd ed. Radnor, PA: Chilton Company, 1972.

Bateson, Robert. Introduction to Control System Technology. Columbus, OH: Charles E. Merrill Publishing Company, 1973.

Benedict, Robert P. Fundamentals of Temperature, Pressure, and Flow Measurements. 2nd ed. New York: John Wiley and Sons, 1977.

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 10 T 4

THERMOCOUPLES

THERMAL APPLICATION OF ENERGY TRANSFORMERS CONCEPT

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

In 1826 Thomas Johann Seebeck discovered that a temperature difference that exists across a junction of two dissimilar metals is accompanied by a purely thermal emf. Since then, this type of junction, known as a "thermocouple," has become widely used as a thermometer.

Thermocouple theory and practical application are presented in this module. Examples are included to demonstrate the use of thermocouple calibration tables and computations necessary to determine temperature for nonstandard thermocouples. In the laboratory, the student will measure the thermoelectric voltage of different thermocouples.

PREREQUISITES

The student should have completed Concept Module 9-0, "Energy Converters."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Sketch a typical thermocouple circuit, and briefly describe how it is used to measure temperature.
- Given the temperature of the reference junction, determine the following from calibration tables for a standard thermocouple:
  - a. Temperature of the test junction from the thermoelectric emf.
  - b. Thermoelectric emf from the temperature of the test junction.
- Calculate the thermoelectric emf of a nonstandard thermocouple.
- Determine the temperature of the test junctions of a thermopile from the thermoelectric voltage.

- Calculate the thermoelectric power of a thermocouple, using the calibration tables.
- Given the appropriate equipment, measure the thermoelectric voltage of different types of thermocouples, and determine the temperature from calibration tables.

DISCUSSION

The thermocouple thermometer usually consists of two junctions of two dissimilar metals A and B, as illustrated in Figure 1. The reference junction R is maintained at a constant, known temperature T_R, and the test junction is the sensor for the unknown temperature T. The thermal emf V (also referred to as the "thermoelectric voltage" and the "thermoelectric emf") developed across the junctions is proportional to the difference in temperature $(T - T_R)$ between the two junctions. The sign of V depends upon which metal is connected to the millivoltmeter; that is, metal A or B. Its polarity changes when the temperature difference $(T - T_R)$ changes polarity.

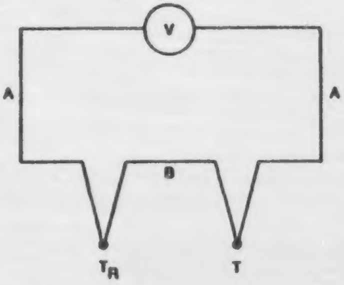


FIG. 1

Calibration tables of thermoelectric voltage as a function of temperature T of the test junction referenced to T_R = 0°C or 32°F are published for the standard thermocouples listed in Table 1 by type and components. Table 2 indicates the composition of alloys commonly used in thermocouples. Table 3 is a partial calibration table for a chromel-alumel thermocouple; Example A demonstrates its use.

TABLE 1. CALIBRATION VOLTAGE FOR THERMOCOUPLES

TYPE	ALLOY COMPOSITION
J	Iron-Constantan
K	Chromel-Alumel
E	Chromel-Constantan
T	Copper-Constantan
S	Platinum vs Platinum - 10% Rhodium
R	Platinum vs Platinum - 13% Rhodium
B	Platinum - 6% Rhodium v Platinum - 30% Rhodium

TABLE 2.COMPOSITION OF THERMOCOUPLE ALLOYS	
ALLOY	COMPOSITION
Chromel	Nickel-Chromium
Alumel	Nickel-Aluminum
Constantan	Copper-Nickel

TABLE 3.CHROMEL - ALMEL THERMOCOUPLES

CHROMEL-ALUMEL THERMOCOUPLES

(Electro-motive Force in Absolute Millivolts. Temperatures in Degrees F.° Reference Junctions at 32° F.)

°F	0	1	2	3	4	5	6	7	8	9
	Millivolts									
−300	−5.51	−5.52	−5.53	−5.54	−5.54	−5.55	−5.56	−5.57	−5.[illegible]	−5.59
−290	−5.41	−5.42	−5.43	−5.44	−5.45	−5.46	−5.47	−5.48	−5.49	−5.50
−280	−5.30	−5.31	−5.32	−5.34	−5.35	−5.36	−5.37	−5.38	−5.39	−5.40
−270	−5.20	−5.21	−5.22	−5.23	−5.24	−5.25	−5.26	−5.27	−5.28	−5.29
−260	−5.08	−5.09	−5.10	−5.12	−5.13	−5.14	−5.15	−5.16	−5.17	−5.18
−250	−4.96	−4.97	−4.99	−5.00	−5.01	−5.02	−5.03	−5.04	−5.06	−5.07
−240	−4.84	−4.85	−4.86	−4.88	−4.89	−4.90	−4.91	−4.92	−4.94	−4.95
−230	−4.71	−4.72	−4.74	−4.75	−4.76	−4.77	−4.79	−4.80	−4.81	−4.82
−220	−4.58	−4.59	−4.60	−4.62	−4.63	−4.64	−4.66	−4.67	−4.68	−4.70
−210	−4.44	−4.45	−4.46	−4.48	−4.49	−4.51	−4.52	−4.53	−4.55	−4.56
−200	−4.29	−4.31	−4.32	−4.34	−4.35	−4.36	−4.38	−4.39	−4.41	−4.42
−190	−4.15	−4.16	−4.18	−4.19	−4.21	−4.22	−4.24	−4.25	−4.26	−4.28
−180	−4.00	−4.01	−4.03	−4.04	−4.06	−4.07	−4.09	−4.10	−4.12	−4.13
−170	−3.84	−3.86	−3.88	−3.89	−3.91	−3.92	−3.94	−3.95	−3.97	−3.98
−160	−3.68	−3.70	−3.72	−3.73	−3.75	−3.76	−3.78	−3.80	−3.81	−3.83
−150	−3.52	−3.54	−3.56	−3.57	−3.59	−3.60	−3.62	−3.64	−3.65	−3.67
−140	−3.36	−3.38	−3.39	−3.41	−3.42	−3.44	−3.46	−3.47	−3.49	−3.51
−130	−3.19	−3.20	−3.22	−3.24	−3.25	−3.27	−3.29	−3.31	−3.32	−3.34
−120	−3.01	−3.03	−3.05	−3.06	−3.08	−3.10	−3.12	−3.13	−3.15	−3.17
−110	−2.83	−2.85	−2.87	−2.89	−2.90	−2.92	−2.94	−2.96	−2.98	−2.99
−100	−2.65	−2.67	−2.69	−2.71	−2.72	−2.74	−2.76	−2.78	−2.80	−2.82
−90	−2.47	−2.49	−2.50	−2.52	−2.54	−2.56	−2.58	−2.60	−2.62	−2.63
−80	−2.28	−2.30	−2.32	−2.34	−2.36	−2.37	−2.39	−2.41	−2.43	−2.45
−70	−2.09	−2.11	−2.13	−2.15	−2.17	−2.18	−2.20	−2.22	−2.24	−2.26
−60	−1.90	−1.92	−1.94	−1.96	−1.97	−1.99	−2.01	−2.03	−2.05	−2.07
−50	−1.70	−1.72	−1.74	−1.76	−1.78	−1.80	−1.82	−1.84	−1.86	−1.88
−40	−1.50	−1.52	−1.54	−1.56	−1.58	−1.60	−1.62	−1.64	−1.66	−1.68
−30	−1.30	−1.32	−1.34	−1.36	−1.38	−1.40	−1.42	−1.44	−1.46	−1.48
−20	−1.10	−1.12	−1.14	−1.16	−1.18	−1.20	−1.22	−1.24	−1.26	−1.28
−10	−0.89	−0.91	−0.93	−0.95	−0.97	−0.99	−1.01	−1.03	−1.06	−1.08
(−)0	−0.68	−0.70	−0.72	−0.75	−0.77	−0.79	−0.81	−0.83	−0.85	−0.87
(+)0	−0.68	−0.66	−0.64	−0.62	−0.60	−0.58	−0.56	−0.54	−0.52	−0.49
10	−0.47	−0.45	−0.43	−0.41	−0.39	−0.37	−0.34	−0.32	−0.30	−0.28
20	−0.26	−0.24	−0.22	−0.19	−0.17	−0.15	−0.13	−0.11	−0.09	−0.07
30	−0.04	−0.02	0.00	0.02	0.04	0.07	0.09	0.11	0.13	0.15
40	0.18	0.20	0.22	0.24	0.26	0.29	0.31	0.33	0.35	0.37
50	0.40	0.42	0.44	0.46	0.48	0.51	0.53	0.55	0.57	0.60
60	0.62	0.64	0.66	0.68	0.71	0.73	0.75	0.77	0.80	0.82
70	0.84	0.86	0.88	0.91	0.93	0.95	0.97	1.00	1.02	1.04
80	1.06	1.09	1.11	1.13	1.15	1.18	1.20	1.22	1.24	1.27
90	1.29	1.31	1.33	1.36	1.38	1.40	1.43	1.45	1.47	1.49

100	1.52	1.54	1.56	1.58	1.61	1.63	1.65	1.68	1.70	1.72
110	1.74	1.77	1.79	1.81	1.84	1.86	1.88	1.90	1.93	1.95
120	1.97	2.00	2.02	2.04	2.06	2.09	2.11	2.13	2.16	2.18
130	2.20	2.23	2.25	2.27	2.29	2.32	2.34	2.36	2.39	2.41
140	2.43	2.46	2.48	2.50	2.52	2.55	2.57	2.59	2.62	2.64
150	2.66	2.69	2.71	2.73	2.75	2.78	2.80	2.82	2.85	2.87
160	2.89	2.92	2.94	2.96	2.98	3.01	3.03	3.05	3.08	3.10
170	3.12	3.15	3.17	3.19	3.22	3.24	3.26	3.29	3.31	3.33
180	3.36	3.38	3.40	3.42	3.45	3.47	3.49	3.52	3.54	3.56
190	3.59	3.61	3.63	3.66	3.68	3.70	3.73	3.75	3.77	3.80
200	3.82	3.84	3.87	3.89	3.91	3.94	3.96	3.98	4.01	4.03
210	4.05	4.08	4.10	4.12	4.15	4.17	4.19	4.21	4.24	4.26
220	4.28	4.31	4.33	4.35	4.38	4.40	4.42	4.44	4.47	4.49
230	4.51	4.54	4.56	4.58	4.61	4.63	4.65	4.67	4.70	4.72
240	4.74	4.77	4.79	4.81	4.83	4.86	4.88	4.90	4.92	4.95
250	4.97	4.99	5.02	5.04	5.06	5.08	5.11	5.13	5.15	5.17
260	5.20	5.22	5.24	5.26	5.29	5.31	5.33	5.35	5.38	5.40
270	5.42	5.44	5.47	5.49	5.51	5.53	5.56	5.58	5.60	5.62
280	5.65	5.67	5.69	5.71	5.73	5.76	5.78	5.80	5.82	5.85
290	5.87	5.89	5.91	5.93	5.96	5.98	6.00	6.02	6.05	6.07
300	6.09	6.11	6.13	6.16	6.18	6.20	6.22	6.25	6.27	6.29
310	6.31	6.33	6.36	6.38	6.40	6.42	6.45	6.47	6.49	6.51
320	6.53	6.56	6.58	6.60	6.62	6.65	6.67	6.69	6.71	6.73
330	6.76	6.78	6.80	6.82	6.84	6.87	6.89	6.91	6.93	6.96
340	6.98	7.00	7.02	7.04	7.07	7.09	7.11	7.13	7.15	7.18
350	7.20	7.22	7.24	7.26	7.29	7.31	7.33	7.35	7.38	7.40

EXAMPLE A: USE OF THERMOCOUPLE CALIBRATION TABLES

Given: A chromel-alumel thermocouple has $T_R = 32°F$ and $V = 2.73$ millivolts.

Find: The temperature of the test junction.

Solution: The temperature in increments of 10°F is listed in the first column of Table 3. Succeeding columns list the thermoelectric voltage as the temperature is increased in steps of 1°F. The emf of 2.73 mV is located in the row labeled 150°F and in the column labeled 3°F. Therefore —

$$T = 150°F + 3°F$$

$$T = 153°F$$

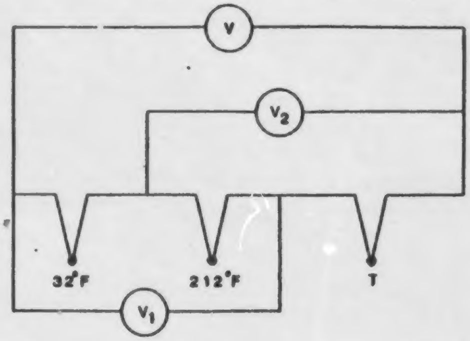
If the temperature of the reference junction is not 32°F, the temperature of the test junction still can be found from the tables referenced to 32°F. Examples B and C illustrate this procedure.

EXAMPLE B: ARBITRARY REFERENCE TEMPERATURE

Given: A chromel-alumel thermocouple has $T_R = 212°F$ and $V = 3.28$ mV.

Find: Temperature T of the test junction.

Solution: The thermocouple circuit can be represented by three junctions, at 32°F, at 212°F, and at the unknown temperature T, all in series. The thermoelectric voltage is the sum of the voltage V_1 between 32°F and 212°F and the voltage V_2 between 212°F and T.



From Table 3, $V_1 = 4.10$ mV; therefore, the sum V is

$$V = V_1 + V_2$$
$$= 4.10 \text{ mV} + 3.28 \text{ mV}$$
$$V = 7.38 \text{ mV}$$

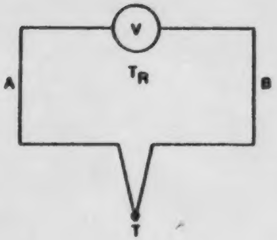
According to Table 3, the temperature corresponding to V = 7.38 mV is T = 358°F.

EXAMPLE C: SINGLE JUNCTION THERMOCOUPLE

Given: The thermoelectric voltage across a single-junction thermocouple is 2.80 mV. Room temperature is 72°F.

Find: The temperature of the test junction.

Solution: The reference temperature for the single junction is the temperature at the meter, or room temperature. Therefore —



$V = V_1 + V_2$

$= 0.88\text{ mV} + 2.80\text{ mV}$

$V = 3.68\text{ mV}$

This value corresponds to T = 194°F.

To calibrate a thermocouple for use at reference temperatures other than 32°F often is desirable. Example D illustrates this procedure.

EXAMPLE D: THERMOCOUPLE CALIBRATION

Given: A chromel-alumel thermocouple has $T_R = 212°F$ and $T = 150°F$.

Find: The thermoelectric voltage V_2 generated.

Solution: From Table 3, V = 4.10 mV between 32°F and 212°F, and V = 2.66 mV between 32°F and 150°F. (Refer back to sketch in Example B.) Therefore —

$V = V_1 + V_2$

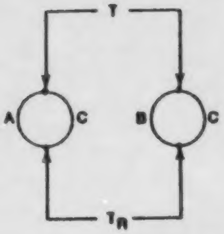
$V_2 = V - V_1$

$= 2.66\text{ mV} - 4.10\text{ mV}$

$V_2 = -1.44\text{ mV}$

The sign reversal indicates that the test junction at 150°F is cooler than the reference junction at 212°F.

Figure 2 shows two separate thermocouples with test and reference junctions at the same temperatures T and T_R. One thermocouple is composed of metals A and C; the other, of metals B and C. For a thermocouple composed of metals A and B, thermoelectric emf is developed per Equation 1.



$$V_{AB} = V_{AC} - V_{BC} \qquad (1)$$

where

V_{AB} = thermoelectric emf developed in a thermocouple of materials A and B.
V_{AC} = thermoelectric emf developed in a thermocouple of materials A and C.
V_{BC} = thermoelectric emf developed in a thermocouple of materials B and C.

This result enables the tabulation of V as a function of T for any thermocouple made of two standard thermocouple metals. Example E illustrates the calibration of such a nonstandard thermocouple.

EXAMPLE E: CALIBRATION OF NONSTANDARD THERMOCOUPLE

Given: A copper-constantan thermocouple with $T_R = 32°F$ and $V = 1.75$ mV at $T = 110°F$, and an iron-constantan thermocouple with $T_R = 32°F$ and $V = 2.23$ mV at $T = 110°F$.

Find: The thermoelectric emf generated across an iron-copper thermocouple at $T = 110°F$ referenced at 32°F.

Solution: A = iron (Fe), B = copper (Cu), C = constantan.

$$\begin{aligned} V_{Fe-Cu} &= V_{Fe-C} - V_{Cu-C} \\ &= 2.23 \text{ mV} - 1.75 \text{ mV} \\ V_{Fe-Cu} &= 0.48 \text{ mV} \end{aligned}$$

Even when thermocouple tables are unavailable, there is a way to compute the thermal emf of a thermocouple, provided the temperatures to be measured are not higher than a few hundred degrees. The thermoelectric emf for a thermocouple consisting of lead (Pb) and any metal M, referenced to 0°C can be calculated from Equation 2.

$$V_{M - Pb} = aT + \frac{1}{2}bT^2 \qquad (2)$$

where

$V_{M - Pb}$ = thermoelectric voltage.
a and b = constants.
T = temperature of the test junction in degrees Celcius.

Table 4 lists values for the constants a and b for several metals. Example F illustrates how the thermoelectric emf for an arbitrary thermocouple is found by using Equations 1 and 2.

TABLE 4

Metal M	a ($\mu V/°C$)	b ($\mu V/°C^2$)
Aluminum	-0.47	0.003
Bismuth	-43.7	-0.47
Copper	2.76	0.012
Gold	2.90	0.0093
Iron	16.6	-0.030
Nickel	19.1	-0.030
Platinum	-1.79	-0.035
Silver	2.50	0.012
Steel	10.8	-0.016

EXAMPLE F: CALCULATION OF THERMOELECTRIC VOLTAGE

Given: An iron-gold thermocouple has $T_R = 0°C$ (32°F) and $T = 100°C$ (212°F).

Find: The thermoelectric emf V.

Solution: For iron (Fe), $a = 16.6\ \mu V/°C^2$ and $b = 0.030\ \mu V/°C$.
For an iron-lead thermocouple —

$$\begin{aligned} V_{Fe - Pb} &= aT + \frac{1}{2}bT^2 \\ &= (16.6\ \mu V/°C)(100°C) + \frac{1}{2}(-0.030\ \mu V/°C^2)(100°C)^2 \\ &= 1510\ \mu V \\ V_{Fe - Pb} &= 1.510\ mV \end{aligned}$$

For gold (Au), a = 2.90 μV/°C, and b = 0093 μV/°C.

$$V_{Au - Pb} = aT + \frac{1}{2}bT^2$$

$$= (2.90\ \mu V/°C)(100°C) + \frac{1}{2}\ (0.0093\ \mu V/°C^2)(100°C)^2$$

$$= 336.5\ \ V$$

$$V_{Au - Pb} = 0.3365\ mV$$

From Equation 1,

$$V_{Fe - Au} = V_{Fe - Pb} - V_{Au - Pb}$$

$$= 1.510\ mV - 0.3365\ mV$$

$$V_{Fe - Au} = 1.1735\ mV$$

A thermopile consists of many thermocouples connected in series. The thermoelectric voltage of the thermopile is the sum of the individual emfs and, therefore, is a larger voltage, much easier to measure. Thermopiles can be used for detecting and measuring low-level radiant energy, such as that from stars. Example G demonstrates how the temperature is determined from thermopile voltage.

EXAMPLE G: THERMOPILE VOLTAGE

Given: The thermoelectric voltage across a thermopile composed of five chromel-constantan thermocouples in series is 0.1 V with reference to 0°C.

Find: The temperature of the test junction.

Solution: The thermoelectric voltage of a single thermocouple is as follows:

$$V = 0.1\ V/5$$

$$= 0.02\ V$$

$$V = 20.0\ mV$$

The temperature corresponding to 20.0 mV in appropriate calibration tables for chromel-constantan is 287°C.

When thermocouple wires are chosen, the calibration tables should be inspected to determine which type covers the range of temperatures to be measured and which is most sensitive to changes in temperature in the range; that is, which exhibits the largest change in thermoelectric emf per degree change in temperature. The important quantity in evaluating the sensitivity of a particular thermocouple is thermoelectric power, often referred to as "thermopower." It is defined as the change in thermoelectric emf per degree change in temperature. Mathematically, this relationship is stated by Equation 3.

$$S = \frac{\Delta V}{\Delta T} \qquad (3)$$

where

S = thermopower.
ΔV = change in thermoelectric voltage.
ΔT = change in temperature of the test junction.

The larger the thermopower at a given temperature, the more sensitive is the thermocouple. Table 5 compares thermopowers of several types of thermocouples at 500°C (932°F) and at -100°C (-148°F). Example H demonstrates computation of thermopower.

TABLE 5. THERMOPOWERS

Type	Composition	S(mV/°C) at 500°C	S(mV/°C) at -100°C
J	Iron-Constantan	0.060	0.040
K	Chromel-Alumel	0.040	0.030
T	Copper-Constantan	*	0.030
S	Platinum vs Platinum-10% Rhodium	0.010	*

* not tabulated at this temperature

EXAMPLE H: THERMOPOWER COMPUTATION

Given: The thermoelectric voltage V for a chromel-alumel thermocouple is 20.65 mV at 500°C and is 20.69 mV at 501°C.

Find: The thermopower S.

Solution: $$S = \frac{\Delta V}{\Delta T}$$

$$= \frac{(20.69 \text{ mV} - 20.65 \text{ mV})}{(501^\circ\text{C} - 500^\circ\text{C})}$$

$$S = 0.04 \text{ mV}/^\circ\text{C}$$

SUMMARY

The typical thermocouple consists of a reference junction at a fixed, known temperature and a test junction at the temperature to be measured. The temperature is determined from published calibration tables or is calculated using one or both of the following equations:

$$V_{AB} = V_{AC} - V_{BC} \qquad (1)$$

$$V_{M-Pb} = aT + \tfrac{1}{2}bT^2 \qquad (2)$$

A thermopile is a series of thermocouples whose thermoelectric voltages add, producing a larger and easier-measured emf. Thermoelectric power is the change in thermoelectric emf per degree change in temperature and indicates the sensitivity of a thermocouple.

LABORATORY

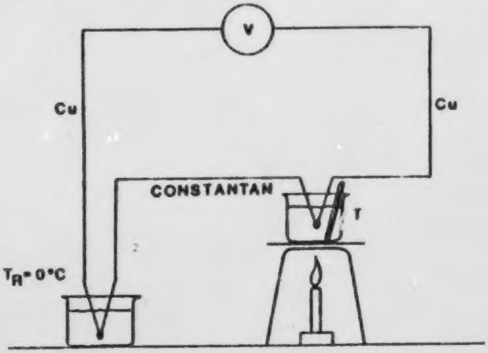
THERMOELECTRIC VOLTAGE OF THERMOCOUPLES

MATERIALS

Iron, copper, and constantan thermocouple wires.
Mercury thermometer.
Millivoltmeter (or potentiometer).
Bunsen burner.
2 beakers.
Ring stand.
Asbestos screen.
Ice.
Thermocouple tables (see references).

PROCEDURE

1. Construct a type T thermocouple from copper and constantan wires, by twisting the opposite ends of a constantan wire onto two separate lengths of copper, as shown in Figure 3. Construct a type J thermocouple from iron and constantan in the same manner. Assemble the apparatus shown in Figure 3.



2. Measure temperature of boiling water in °C with mercury thermometer, and record in Data Table. Measure thermoelectric emf of each thermocouple with millivoltmeter, and record in Data Table.

3. Determine temperature of boiling water from calibration tables for each thermocouple, and record in the results section of Data Table. If necessary, use the following equation to convert degrees Fahrenheit to Celcius:

$$T_C = \frac{5}{9}(T_F - 32°)$$

4. Repeat Steps 2 and 3 with reference junctions and mercury thermometer at room temperature.

5. From T and J thermocouples, make an iron-copper thermocouple. Repeat Step 2, using ice water as a reference.

6. Determine thermoelectric voltage of iron-copper thermocouple from measured emf's for iron-constantan and copper-constantan (Step 2), using Equation 1:

$$V_{AB} = V_{AC} - V_{BC}$$

where
A = iron.
B = copper.
C = constantan.

Record in the results section of Data Table and compare with the measured value of Step 5.

7. Calculate thermoelectric voltage of iron-copper thermocouple, using the coefficients in Table 4 and Equations 1 and 2:

$$V_{M - Pb} = aT + \tfrac{1}{2}bT^2 \qquad (2)$$

$$V_{AB} = V_{AC} - V_{BC} \qquad (1)$$

where
A = iron.
B = copper.
C = lead.
T = temperature read from mercury thermometer in degrees Celcius.

Record under results, and compare with the values measured in Step 5 and computed in Step 6.

8. Explain any differences between the two values.

DATA TABLE	
MEASUREMENTS	RESULTS
Boiling point from mercury thermometer:	
T = ________ °C	
Reference at 0°C:	
Type J (iron-constantan) V = ________ mV	T = ________ °C
Type T (copper-constantan) V = ________ mV	T = ________ °C
Reference at room temperature: T_R = ________ °C	
Type J (iron-constantan)V = ________ mV	T = ________ °C
Type T (copper-constantan) V = ________ mV	T = ________ °C
Iron-copper thermocouple V = ________ mV	V (Step 6) = ________ mV
	V (Step 7) = ________ mV

SELF CHECK

1. Sketch a typical thermocouple circuit, and briefly describe how it is used to measure temperature.

2. A thermoelectric emf of 6.92 mV is read across a copper-constantan thermocouple. Find the temperature of its test junction if its reference temperature is (a) 32°F or (b) 70°F.

3. The temperature of the test junction of a platinum-versus-platinum, 10% rhodium thermocouple is 1500°C. Find the thermoelectric voltage if the reference temperature is 0°C.

4. The test junction temperature of an iron-copper thermocouple is 300°C. For a reference temperature of 0°C, calculate the thermoelectric voltage (a) from calibration tables of iron-constantan and copper-constantan thermocouples and (b) from the equation for lead thermocouples.

5. Find the temperature of the test junctions of a thermopile consisting of five iron-constantan thermocouples with reference at 0°C, if the thermoelectric voltage is 0.1 V.

6. Find the thermopower of an iron-constantan thermocouple at T = 264°C. Use calibration tables.

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UNIFIED TECHNICAL CONCEPTS

MODULE 10 T 5

THERMISTORS

THERMAL APPLICATION OF TRANSDUCERS

Technical Education Research Center – Southwest

TERC - SW

INTRODUCTION

The thermistor is a semiconductor transducer device whose resistance varies considerably with temperature. The resistance of some thermistors increases with a temperature increase, while that of others decreases with the same temperature increase. A thermistor exhibits characteristics that permit its straightforward application to many sensing, measurement, and control problems that otherwise would require elaborate equipment and complex circuitry. It is one of the simplest and most versatile components available for use by the electronics designer and by industry. This module explores the construction, operation, and applications of this functional component. In the laboratory, the student will measure the increase or decrease in thermistor circuits.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:

  Thermistor.
  Self-heated mode.
  Externally-heated mode.
  Resistance-temperature characteristic.
  Voltage-current characteristic.
  Current-time characteristic.

- Describe how the thermistor is used for temperature measurement, temperature control, liquid level control, and time delay.

- Make a calibration graph for converting thermistor resistance into temperature measurements.

- Using a thermistor calibration graph, select the resistance values for five different temperatures and the temperatures for five different resistances.
- Select an application for a thermistor from several system choices.
- Select from four possibilities the correct determination of the sensitivity of a thermistor.
- Given the appropriate equipment, measure the increase or decrease in thermistor circuits, and plot resistance versus temperature for these circuits.

DISCUSSION

The thermistor [therm(o)- + (res)istor] is a semiconductor device. It has the unique property that its resistance varies with temperature, increasing in some types, decreasing in others. Resistance in any electrical resistor will change as the temperature varies, but the resistance change generally is small and negligible. However, the resistance of a thermistor is unique: it changes substantially with temperature variation. Thus, the thermistor behaves as a "thermal resistor"; that is, as a resistor with a high temperature coefficient of resistance.

The temperature coefficient of resistance of a material is given by Equation 1.

$$\alpha = \left(\frac{\Delta R}{R_S}\right)\left(\frac{1}{\Delta T}\right) \qquad (1)$$

where

α = temperature coefficient of resistance.
ΔR = change in resistance when temperature is changed by an amount ΔT.
R_S = resistance of material at the reference temperature.
ΔT = change in temperature above the reference temperature.

For instance, the temperature coefficient of resistance for iron is 50×10^{-4}. For nichrome, it is 2×10^{-4}; and for silver, 38×10^{-4}. Thus, iron increases its resistance per degree rise in temperature about 25 times as much as nichrome. However, thermistors have still a much higher α value than any given here.

Notice that all the numbers given above should have units of 1/C°; that is, reciprocal Centigrade degrees. Since $\alpha = (\Delta R/R)(1/\Delta T)$, the only units that remain are associated with $1/\Delta T$, hence the units of reciprocal Centigrade degrees. A convenient way of reading the values for the temperature coefficient is simply to say "50×10^{-4} per Centigrade degree" for iron and "38×10^{-4} per Centigrade degree" for silver, and so on.

The high sensitivity to temperature causes thermistors to change their resistance by as much as 6% of their normal value for each °C temperature variation. This sensitivity makes the thermistor a useful component in temperature measurement, in temperature sensing and control, and in temperature compensation applications.

Thermistors are semiconductor devices made of ceramic materials mixed (doped) with various grades or mixtures of metalic oxides such as the oxides of manganese, nickel, cobalt, copper, iron, and uranium. After the raw materials are milled and mixed in accurate proportions, suitable binding materials are added, and the units are pressed or extruded to the desired shape.

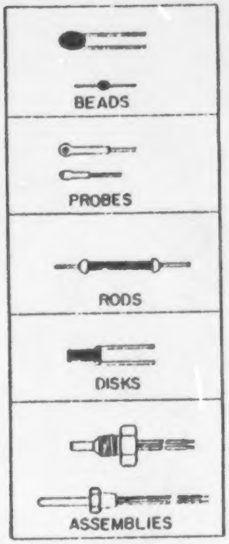


FIG. 1

Thermistor elements then are sintered (heated) under carefully-controlled atmospheric and temperature conditions to produce the ceramic semiconductor material. Electrode materials and lead wires then are attached. Figure 1 shows some common thermistor forms available today.

THERMISTORS

Both negative-temperature-coefficient (NTC) and positive-temperature-coefficient (PTC) materials are used in the manufacture of thermistors. For negative (NTC) thermistors, the resistance decreases with temperature; for positive (PTC) thermistors, the resistance increases with temperature. Figure 2 shows the resistivity of both NTC and PTC materials, over a range of temperatures, as compared to that of a metallic conductor (platinum). Recall that resistivity is a constant for any material and is defined in Equation 2.

$$R = \frac{\rho \ell}{A} \qquad (2)$$

where

R = resistance in ohms.
ℓ = length (in convenient units).
A = cross-sectional area in the same convenient units.

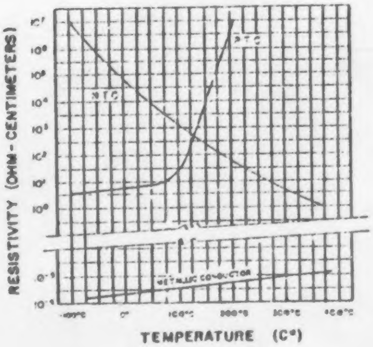


FIG. 2

Thus ρ, the resistivity, is measured in ohm-centimeters if ℓ is in centimeters and A is in (centimeters)^2. In some types of thermistor materials, the resistance is doubled with a temperature change of as little as one degree Centigrade(°C)! PTC type thermistors have a very limited and specialized application. Since the resistance curve for PTC thermistors is abrupt and nonlinear, these thermistors can be used in motor controls and for protection against overheating.

Figure 2 also graphically illustrates the wide range of resistances available in NTC materials.

MODES OF OPERATION

There are two modes of thermistor operation — "self-heated" and "externally-heated." Externally-heated, thermistors convert changes in ambient or contact temperatures directly to corresponding changes in voltage or current flow. These thermistors are well-suited for precision temperature measurement, temperature control, and temperature compensation, because they exhibit large changes in resistance with temperature. They are widely used for applications in the range of -100°C to over 300°C.

Self-heated NTC thermistors employ the heating effect of the current flowing through them to raise and control their temperature, and, thus, to decrease their resistance dramatically. Under normal operating conditions, the temperature can rise 200 C° to 300 C°, and the resistance at high current can be reduced to 1/1000 its value at low current. This mode of operation is useful in devices such as voltage regulators, microwave power meters, gas analyzers, vacuum gages, flowmeters, and automatic volume and power-level controls. By careful circuit design, almost any desired time lag can be introduced in the response of self-heated thermistors, thus making them useful in time-delay and surge-suppression applications.

CHARACTERISTICS OF THERMISTORS

Three important characteristics of thermistors make them useful in electronic and electrical circuits:

(1) Resistance-temperature characteristic.
(2) Voltage-current characteristic.
(3) Current-time characteristic.

RESISTANCE-TEMPERATURE CHARACTERISTIC

Since thermistors exhibit a large change in resistance when subjected to a small increase or decrease in temperature, they are very accurate temperature-sensing devices. Thermistors can be placed in remote locations, because long electrical-wire leads can be used on the ohmmeter. For convenience, the ohm-meter scale usually is calibrated to read temperature directly.

VOLTAGE-CURRENT CHARACTERISTIC

Self-heating thermistors can be used to control current in a circuit. In these thermistors, a heavy current flow causes an increase in resistance as the thermistor heats up. This increased resistance lowers the current and tends to keep it constant. The current can be set at any desired level by using a variable resistor that can be calibrated to the current desired.

CURRENT-TIME CHARACTERISTIC

Since time is required for thermistors to heat up, they can be used for time-delay switches. Time delay can be controlled by means of a variable resistor calibrated in seconds (or other time units).

THERMISTOR APPLICATIONS

As there are so many circuits in which thermistors are used to great advantage, only a few of the more common applications are described.

TEMPERATURE-MEASUREMENT

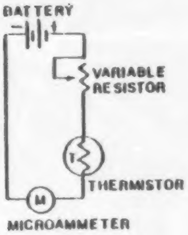


FIG. 3

The simple circuit for temperature measurement illustrated in Figure 3 consists of a battery, a variable resistor, a thermistor, and a microammeter. As the temperature changes, the resistance of the thermistor changes; and the current flow through the meter can be calibrated in terms of temperature. The resistor can be adjusted to compensate for battery age. In this circuit, the thermistor can be mounted a great distance from the meter, and ordinary copper wire can be used for the connections.

TEMPERATURE CONTROL

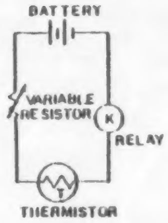


FIG. 4

Simple temperature control can be made by placing a thermistor in series with a relay, a battery, and a variable resistor, as illustrated in Figure 4. When the current is large enough, the relay will open (or close). The current can be adjusted by the variable resistor to actuate the relay at the desired thermistor temperature.

LIQUID LEVEL CONTROL

If a thermistor is placed in series with a relay and a battery, the relay can be made to operate if the thermistor is suspended in air (higher temperature) and to drop out when the thermistor is immersed in liquid (lower temperature). This situation is shown in Figure 5. In air, the NTC thermistor heats up, causing the resistance to drop and permitting enough current to flow to pull in the relay. If the thermistor is submerged in a liquid, it will be cooled, causing its resistance to increase. As a result, the current through the relay is reduced to a point at which the relay is no longer actuated. This device can be used as a liquid-level indicator or as a liquid-level control device.

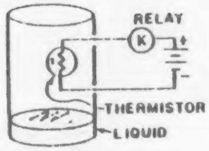


FIG. 5

TIME DELAY

If a thermistor is placed in series with a variable resistor, a battery, and a relay as shown in Figure 6, a variable time-delay relay can be made. When the switch is closed, current flow is limited by the high resistance of the thermistor, until it heats up and permits sufficient current to flow to close the relay. An increase in circuit resistance increases the time delay. With proper selection of components, time delays from milliseconds to many seconds can be produced.

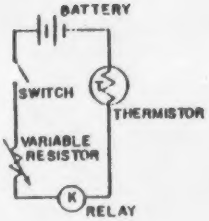


FIG. 8

TESTING OF THERMISTORS

The equipment used to test thermistors must possess a measurement capability corresponding to the precision desired in measuring thermistor characteristics. Where applications or trouble-shooting measurements are made, any instrument that has a low-power ohm-function can be used. A digital VOM or a FET VOM is suggested for use, rather than the common Triplett or Simpson meters which contain a 1.5-volt battery. Current from a 1.5-volt battery can cause self-heating of the thermistor, and this will make the readings inaccurate.

SUMMARY

A thermistor is a resistive element whose resistance changes substantially in response to its temperature. It is a semiconductor device constructed of ceramic materials doped with various mixtures of metallic oxides. Some thermistors are self-heated, or heated by the current through them, and often are used to control current flow or to produce a time delay. Others are heated externally, or heated by ambient or contact heat, and are employed in temperature-measurement and control systems. Though simple, thermistors perform valuable functions, which if duplicated by other components would require elaborate equipment and complex circuitry.

RESISTANCE/TEMPERATURE CHARACTERISTICS OF A THERMISTER

MATERIALS

VOM.
Thermistor.
Ice.
Boiling water.
Two beakers.
Bunsen burner, ring stand, and wire gage.
Supply of hot, cold, and mixed tap water.
Laboratory thermometer.

PROCEDURE

In this experiment, the student will make a resistance-temperature graph for a thermistor in order that it can be used to measure temperature.

1. Connect VOM leads to thermistor, and record resistance of thermistor at room temperature (in air). In Data Table 1, record room temperature (as shown on a laboratory thermometer).
2. Place thermistor and thermometer in a container of melting ice. Record resistance and temperature.
3. Place thermistor and thermometer in a container of boiling water. Record resistance and temperature.
4. Record resistance and temperature for thermistor and thermometer in tap water from cold water tap, from hot water tap, and from both taps mixed.
5. Record type of thermistor and type of VOM.
6. Plot resistance versus temperature on the graph in Data Table 2. Carefully draw a smooth curve, connecting the data points plotted and extending the curve to the sides of the graph. (Semi-log axis is used for resistance values, because resistance covers such a wide range of values.)
7. Explain the significance of the data plotted and some industrial applications of this thermistor.

RESISTANCE CHANGES OF A THERMISTOR

MATERIALS

Thermistor (same as in first experiment).
Ice.
Boiling water.
No. 1449 bulb and socket.
d.c. power supply or battery (variable-voltage capacity).
Two beakers.
Bunsen burner, ring stand, and wire gage.
Thermometer.

PROCEDURE

Assemble circuit shown in Figure 7, using a No. 1449 bulb and socket, a thermistor, and a variable-voltage power supply.

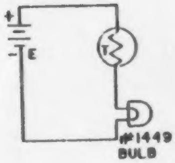


FIG. 7

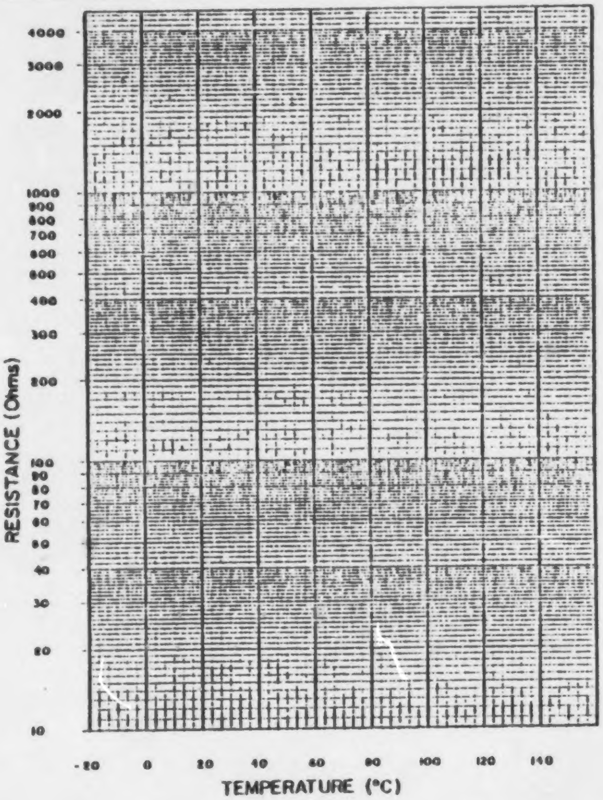
Note brilliance of the lamp at room temperature. Expose thermistor to cold (touch it to the ice water) and then to hot (touch it to the boiling water). At each temperature extreme, note the lamp brilliance. From these observations, analyze the operation of the thermistor in this circuit. CAUTION: Use a voltage as low as possible to light the bulb with the thermistor at room temperature. Do not change this voltage setting during the experiment.

DATA. TABLE 1

Situation	Thermometer Reading (°C)	R (Ohms)
Room temperature		
Ice water		
Boiling water.		
Cold tap water		
Hot tap water		
Mixed tap water		

Type of thermistor ________________________________.
Type of VOM ________________________________.

DATA TABLE 2



TYPE OF THERMISOR ________ TYPE OF VOM ________

DATA TABLE 3

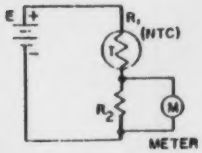
Temperature	Resistance (Ω)	Resistance	Temperature (°C)
15°C		500 Ω	
80°C		1500 Ω	
40°C		900 Ω	
25°C		2000 Ω	
60°C		1250 Ω	

SELF CHECK

1. Define these terms:

   Thermistor.
   Self-heated mode.
   Externally-heated mode.
   Resistance-temperature characteristic.
   Voltage-current characteristic.
   Current-time characteristic.

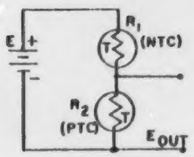
2. Describe how the thermistor is used for temperature measurement, temperature control, liquid level control, and time delay.



3. Using the thermistor calibration graph drawn in the laboratory, fill in Data Table 3.

4. In the adjoining circuit, how will the voltage across resistor R_2 vary if the temperature decreases?

   Increases?
   Decreases?
   Remains the same?



5. In the adjoining circuit R_1 and R_2 are thermistors with resistances at room temperature and identical characteristics. The only difference is that one has an NTC, and the other has a PTC. If the temperature increases, how will the output voltage E_{out} change?

   Increases?
   Decreases?
   Remains the same?

6. In a positive temperature thermistor, a temperature increase causes what change in the resistance?

   Increases?
   Decreases?
   Remains the same?

7. Which of the following would not be a possible application for a thermistor?

   Electronic thermometer.
   Fire detection and warning system.
   Fuse.
   Temperature control for PTC components.

8. The sensitivity of a thermistor is determined by which of the following?

Its rate of power dissipation.
Its reaction to self-heating effects.
Its ability to respond to a wide temperature range.
The amount of resistance change for a given temperature variation.

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 10 T 6

PYROMETERS

THERMAL APPLICATION OF TRANSDUCERS

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

A body when heated emits thermal radiation in the infrared or visible parts of the spectrum. Measurement of either total power radiated or color associated with thermal radiation provides a noncontact method for determining temperature of the hot body. A device known as a pyrometer is especially useful in making appropriate measurements if the body temperature is high.

In this module, the student will use pyrometers to perform noncontact temperature measurements.

PREREQUISITES

Student should have completed Concept Module 10-0, "Transducers."

OBJECTIVES

To complete this module, the student should be able to:

- Define emissivity, Stefan-Boltzmann constant and blackbody radiation.
- State mathematical relationship between temperature of a heated body and emission of thermal radiation and explain each term, as well as indicate how this relationship can form the basis for a radiation pyrometer.
- Describe relationship between color of a heated body and its temperature and indicate how this relationship can form the basis for an optical pyrometer.
- Describe operation of a radiation pyrometer and an optical pyrometer.
- Use a pyrometer to measure temperatures of heated bodies.

DISCUSSION

The word pyrometer can be applied to many different types of temperature-measuring devices, including thermocouples. In this module, however, we shall adopt the more restricted definition of pyrometer. We shall consider pyrometers to be noncontact temperature-measuring devices that respond to certain characteristics of electromagnetic radiation emitted by the object whose temperature is to be measured. Further, we shall use pyrometers as devices for measurement of relatively high temperatures. For measurement of lower temperatures, other devices such as thermocouples or resistance thermometers would be more appropriate. Clearly, when temperature becomes high, noncontact or pyrometric methods are more appropriate.

The physical basis for the operation of pyrometers is found in emission of radiation by all heated bodies. Any heated body emits thermal radiation. Such emission is a form of electromagnetic radiation, similar in nature to radio waves or light waves. Figure 1 shows thermal radiation emitted by a certain body that has been heated by passing electric current through a resistor embedded in the body.

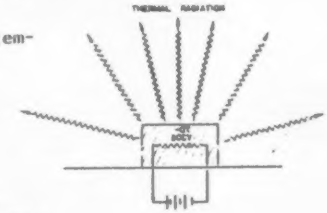

Fig. 1

The amount of radiation emitted increases with body temperature according to the following equation:

$$P = \sigma A \varepsilon T^4$$

where

P = energy per unit time or power (watts) emitted by body.
T = absolute temperature, degrees Kelvin.
A = radiating surface area of heated body, cm^2.
σ = constant called the Stefan-Boltzmann constant, which is numerically equal to 5.669×10^{-12} $w/cm^2\text{-deg}^4$.
ε = surface parameter called emissivity.

Emissivity (a dimensionless number) is a quantity that describes emissive power of the surface. It is the ratio between radiant energy emitted by the surface of the body in question and radiant energy that would be emitted by the surface of a perfect radiator at the same temperature.

Emissivity can have any value between 0 and 1. In the limiting case of $\varepsilon = 1$, we have what is called a blackbody. A blackbody at any specified temperature emits the maximum possible radiant power from a given area. It can thus be considered a perfece emitter of radiant energy. In actual practice, there is no real substance that behaves like a perfect blackbody. Some substances, however, such as soot or lampblack, are reasonably close approximations, since they have values of emissivity close to 1. Many other practical substances have values of emissivity that are considerably lower.

Table 1 lists values of emissivity for some substances of interest. Shiny, unoxidized metallic surfaces typically have quite low values of emissivity, much smaller than 1. Normally, when the surface of a metal is oxidized, emissivity increases. Emissivity may also depend on temperature. Note that some materials listed have values of emissivity that are not much less than 1. Examples A, B and C show how Equation 1 applies to different radiant emission calculations.

TABLE 1. EMISSIVITY FOR SEVERAL MATERIALS

Material	(Dimensionless) Emissivity
Aluminum (unoxidized, 300°K)	0.022
Nickel (unoxidized, 300°K)	0.045
Tungsten (unoxidized, 300°K)	0.024
Lead (unoxidized, 300°K)	0.05
Tin (unoxidized, 300°K)	0.043
Steel (unoxidized, 300°K)	0.08
Lead (500°K)	0.08
Tin (500°K)	0.11
Steel (oxidized)	0.80
Granite	0.44
Hard rubber	0.92
Porcelain	0.92

Radiation emitted by heated bodies is spread over a broad range of wavelengths, covering microwave, infrared and, in some cases, visible regions of the spectrum. For comparison purposes, the visible portion of the electromagnetic spectrum lies at wavelengths between 0.4 and 0.7 micrometers. At wavelengths greater than 0.7 micrometers, there is infrared radiation, which is invisible to the human eye but which may be detected by the sensation of warmth that it produces on the human skin.

Details of wavelength distribution of thermal radiation are beyond the scope of this module. We simply illustrate (Figure 2) the manner in which the spectral distribution of radiant power changes with increasing temperature, over the spectral range cov-

EXAMPLE A: RADIANT POWER CALCULATION

Given: Equation 1 and an object with $\epsilon = 1$ and with surface area 10 cm^2 at a temperature of 727°C.

Find: Amount of radiant power emitted.

Solution: Absolute temperature is 727 + 273, or 1000°K. From Equation 1,

$$P = \sigma A \epsilon T^4, \text{ or}$$

$$\text{Power} = 5.669 \times 10^{-12}\ w/cm^2\text{-deg}^4 \times 10\ cm^2 \times 1 \times (1000\ \text{deg})^4$$

$$P = 56.69 \text{ watts.}$$

EXAMPLE B: EMISSIVITY CALCULATION

Given: A body at temperature 500°K emits radiant power density of 1.17 watts/cm^2.

Find: Emissivity.

Solution:

Since $P = \sigma A \epsilon T^4$, we have

$$P/A = 1.17\ w/cm^2 = \epsilon \times 5.669 \times 10^{-12}\ w/cm^2\text{-deg}^4 \times (773\ \text{deg})^4$$

$$1.17 = 2.02\ \epsilon.$$

Thus:

$$\epsilon = 1.17/2.02 = 0.58.$$

EXAMPLE C: RADIATION EMISSION CALCULATION

Given: Absolute temperature of a body increases 10%.

Find: Percentage of radiant emission increase.

Solution: Radiant emission increases by a factor of $(1 + 0.1)^4 = 1.464$, an increase of 46.4%.

ering visible and near infrared portions of the spectrum. Spectral radiant intensity is plotted in relative units and is power per unit surface area per unit wavelength interval, as a function of wavelength. Note that total radiant power (the area under the curve) increases very rapidly as temperature increases.

This is in agreement with the fourth power law expressed by Equation 1. In addition, spectral distribution changes with the peak wavelength shifting toward shorter wavelengths as temperature increases. Thus, for a temperature of 1400°K, there is very little radiant energy within the visible region (0.4 to 0.7 micrometers), whereas, for a temperature of 2600°K, a considerable amount of energy falls within this region.

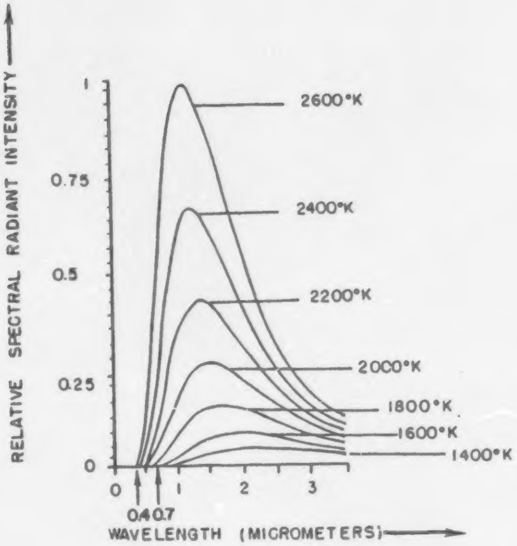

Fig. 2

The color of a heated body as viewed in the emitted radiation is dependent on body temperature. For a heated body to be visible because of its emitted radiation, some radiation with wavelength in the visible region must be present. As temperature is increased gradually, the body first glows with a dull red color, then a bright red and eventually a bluish white color. Color changes because the radiation includes relatively more energy at shorter wavelengths as temperature increases. Table 2 illustrates progression of color change as temperature increases.

TABLE 2. APPARENT COLOR OF HEATED BODIES

Temperature	Color
475°C	Dull red
700°C	Dark red
900°C	Bright red
1100°C	Yellowish-red
1200°C	Yellow-white
1400°C	White
1550°C	Blue-white

In measurement of radiation from heated bodies, one is interested in limited intervals of wavelength and may consider emissivity as a function of wavelength because, for many practical cases, emissivity does change considerably over the total wavelength interval within which the body is emitting. Thus, one has the concept of an emissivity for unit wavelength interval, that is, a spectral emissivity, in contrast to the total emissivity defined earlier. Spectral emissivity is the ratio of power per unit area emitted by the body within a narrow spectral interval divided by power per unit area emitted within the same narrow spectral interval by a blackbody at the same temperature. Table 3 presents some values of spectral emissivity at the wavelength of 0.65 micrometers, a wavelength often used for measurement.

TABLE 3. SPECTRAL EMISSIVITY

Material	Spectral Emissivity Values for Wavelength 0.65 um
Carbon (unoxidized)	0.85
Nickel (unoxidized)	0.36
Tungsten (unoxidized)	0.43
Steel (unoxidized)	0.35
Steel (oxidized)	0.80
Aluminum oxide	0.30
Black felt	0.86
Tungsten (1400°K)	0.453

Thermal radiation emitted by heated bodies leads to a method for determining temperature of the body through a measurement of the amount of radiation. This measurement does not require contact between the measuring device and the hot body so that high temperatures, or temperatures of moving or inaccessible objects may be determined. There are basically two types of measurements that may be performed, taking advantage either of total amount of radiation emitted, according to Equation 1, or of dependence of spectral characteristics of the radiation on the hot body temperature.

The first type of measurement, which essentially measures total radiant emission, uses a device called a radiation pyrometer. Basic structure of a common type of radiation pyrometer is shown in Figure 3. Since one knows the relation between total radiation from the surface of the body and its temperature, measurement of the radiation is enough to determine temperature. In Figure 3, we see radiation collected by a concave mirror and focused on a radiation-sensing element, indicated in this figure

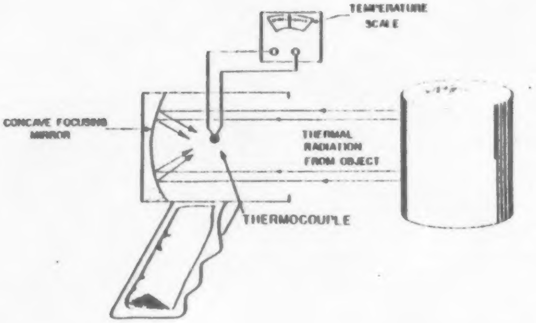

Fig. 3

as a thermocouple. The radiation is collected and heats the thermocouple. Heating of the thermocouple by the radiation leads to generation of a voltage as described in Module 10-0. Therefore, temperature increase of the thermocouple is proportional to radiation received, which, according to Equation 1, is proportional to the fourth power of the temperature of the heated body. One must also include a subtractive term proportional to the fourth power of the surrounding background temperature, typically around 300°K, because the thermocouple also absorbs background radiation. In many cases of high temperature, this term will be negligible.

Over a reasonable range, measurement does not depend on distance between pyrometer and hot body. As one moves farther from the body, the amount of radiation collected by the pyrometer decreases. Size of the image of the hot body formed by the mirror also decreases in the same ratio. Since the image is always larger than the sensor, power received by the sensor will not change and measured value will be independent of distance.

Practical use of a radiation pyrometer depends on knowing the emissivity of the surface. If surface emissivity is less than 1, apparent temperature will be lower than actual temperature because the pyrometer receives less radiation than would be emitted by a blackbody. Figure 4 shows relation between true temperature and observed temperature for various values of the emissivity. For emissivity equal to 1, the observed temperature equals the true temperature (see dashed lines in Figure 4, for example, showing both true and observed temperature equal to 1000°C). For values of emissivity less than 1, 0.6, for example, true temperature (2000°C, for example) is higher than observed temperature (1700°C, for example), with difference becoming greater as emissivity becomes smaller. Thus, for practical use of the radiation pyrometer, one must have knowledge of the emissivity of the surface.

Requiring knowledge of the emissivity can be a source of uncertainty in the measurement because emissivity depends on many conditions, including temperature, surface roughness, particle size for ceramic materials and state of surface oxidation. Moreover, surface oxidation can vary with time for materials heated to high temperatures. These factors mean that temperature measurement with radiation pyrometers can have a fairly large source of error, unless careful calibration against surfaces of similar structure is carried out at known temperatures (Example D).

An optical pyrometer measures thermal energy emitted within a narrow wavelength interval by matching apparent color of the object to color of a filament heated by an electrical current. This measurement makes use of the fact that apparent color of a heated body changes with temperature and that, within a given narrow wavelength interval, the amount of radiation emitted increases with temperature. The optical pyrometer is illustrated in Figure 5. It is similar to a low-power telescope with the filament located in the common focal plane of the two lenses. A piece of red glass is located between lamp and eyepiece. The red glass transmits light only in a narrow spectral interval, usually chosen to be around 0.65 micrometers. When the telescope is focused on a heated glowing object, the image of the target is formed. The observer, view-

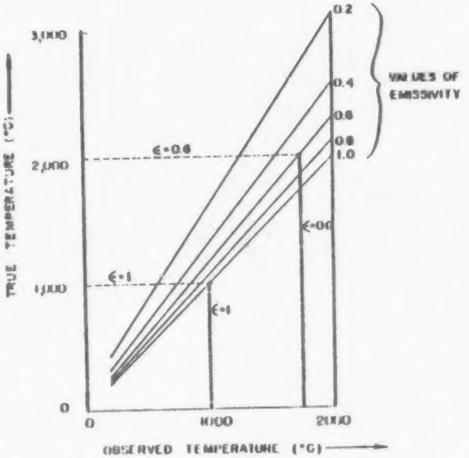

Fig. 4

EXAMPLE D: TRUE TEMPERATURE CALCULATION

Given: A material with $\epsilon = 0.5$ and temperature observed with a radiation pyrometer of 600°C.

Find: True temperature.

Solution: Using Figure 4, and interpolating halfway between the curves for $\epsilon = 0.4$ and $\epsilon = 0.6$ at 600°C, we obtain a true temperature of 760°C.

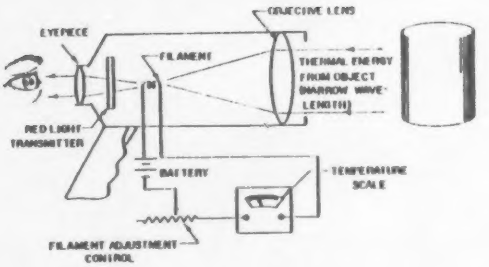

Fig. 5

ing through eyepiece and red glass, sees the image of the lamp filament superimposed on the image of the heated body. By adjusting current to the lamp filament, brightness of the lamp filament is varied until it matches that of the target and seems to disappear against the background of the target. Thus, this type of operation is sometimes called a disappearing filament optical pyrometer.

Temperature is determined by a measurement of current. The pyrometer can be calibrated by viewing a blackbody target at known temperatures. Thus, the meter reading of the current in the matched condition can be calibrated to read a blackbody temperature directly.

As with the radiation pyrometer, the effect of varying emissivity is important. The optical pyrometer gives an observed value of temperature that is equal to the true value of temprature only if the spectral emissivity is equal to unity. If spectral emissivity in the narrow wavelength range in which the measurement is carried out is less than unity, observed temperature will be lower than true temperature and a correction must be applied. The correction is made with a table or graph in the same manner as was described for the radiation pyrometer. A typical set of correction curves is presented (Figure 6).

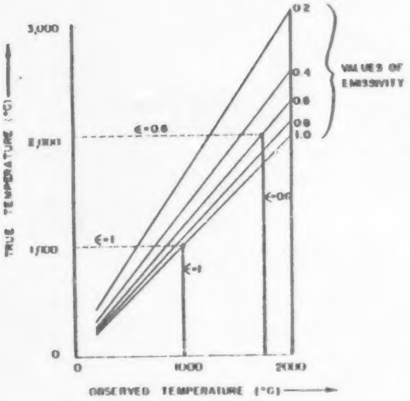

Fig. 6

Because the optical pyrometer requires the body to be glowing visibly, it is useful at a higher range of temperature than is the radiation pyrometer. The low temperature limit for practical measurements with an optical pyrometer is around 700 to 800°C. Above target temperatures of 1300 or 1400°C, an additional absorbing glass filter can be placed between the filament and the objective lens. This reduces apparent brightness of the target to a level that can again be matched by the filament and read on the meter recalibrated for the higher temperature range. Thus, the range of the optical pyrometer can be extended to higher temperature values.

LABORATORY

MATERIALS

Radiation pyrometer (model HSA-4E from William Wahl Company, or equivalent).
Bunsen burner.
Crucible.
Stand and brackets to support crucible.
Lead and tin metal.
Optical pyrometer (Leeds and Northrup series 8627 or equivalent).
Tube furnace capable of reaching 1000°C or more (Lindberg model 55035 or equivalent); furnace should have temperature sensor and display).
Tungsten metal sheet.

PROCEDURE

The procedure presented will assume use of pyrometers as described in the materials list. If different types of pyrometers are employed, instructions may vary somewhat. Consult instructor and instructions supplied by instrument manufacturer and follow their guide.

1. Set crucible on stand; add metallic lead. Heat lead with bunsen burner until lead begins to melt. When material is partially melted, and liquid and solid lead are present simultaneously, material should be at a temperature of melting point of lead.
2. Sight radiation pyrometer on sample. Make sure that sample fills field of view of pyrometer. Set pyrometer dial to known emissivity of lead. (Use Table 1 for emissivity at 500°C.) Obtain temperature from meter reading. (For models of pyrometer for which emissivity cannot be dialed in, use Figure 4 to correct observed temperature and obtain true temperature.)
3. Repeat above procedures with tin metal in crucible.
4. Compare temperatures obtained to known melting points of lead and tin, 327 and 232°C, respectively.
5. Set tungsten metal sheet within tube furnace and turn furnace on. Monitor temperature with thermocouple sensor built into furnace.
6. For some value of temperature in furnace at which sample has begun to glow, sight optical pyrometer on sample. Vary filament current until filament disappears against background of sample. Observe temperature reading on pyrometer display.

7. Increase temperature in furnace; repeat step 6. Obtain temperature measurements with pyrometer at several different furnace temperatures.
8. Correct temperature readings obtained with pyrometer, using spectral emissivity of tungsten from Table 3 for 1400°K spectral emissivity. (Use manufacturer's calibration curves. If these are not available, use Figure 6.)
9. Compare temperature readings obtained with pyrometer with those indicated on the furnace's meter. Discuss possible sources of difference.

SELF CHECK

1. Define or describe pyrometer, emissivity and blackbody.
2. Describe operation of a radiation pyrometer and an optical pyrometer.
3. State mathematical relation between temperature of a heated body and emission of thermal radiation; explain each term.
4. With an optical pyrometer, one observes a temperature of 1800°C for a heated body known to have an emissivity of 0.6. What is the true temperature?
5. A body with surface area 50 cm^2 at a temperature of 1150°K emits 212.2 watts of thermal radiation. What is its emissivity? What will the thermal radiation be if temperature is increased to 1300°K?
6. You are told that a heated body at a temperature of 327°C emits 1 watt of thermal radiation from each square centimeter of its surface. You conclude that something is wrong. Why?

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